Flávio Issao Kubota

MODULARITY IN DESIGN AND MODULARITY IN PRODUCTION: AN ANALYSIS THROUGH A THEORETICAL FRAMEWORK AND A FIELD INVESTIGATION IN TWO AUTOMAKERS

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Supervisor: Prof. PhD. Paulo Augusto Cauchick Miguel
Co-supervisor: Prof. PhD. Juliana Hsuan

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This thesis was judged proper for the achievement of the Doctoral degree in Production Engineering and accepted in its final version by the Post-Graduation Program in Production Engineering.

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Prof. Fernando Forcellini, Dr.
Coordinator – PPGEP-UFSC

Examination Board:

____

Prof. Paulo Augusto Cauchick Miguel, PhD.
Supervisor / Board President
Universidade Federal de Santa Catarina – UFSC

____

Prof. Edson Pinheiro de Lima, Dr.
Pontifícia Universidade Católica do Paraná – PUC/PR (Via Videoconference)

____

Prof. Daniel Pacheco Lacerda, Dr.
Universidade do Vale dos Sinos – UNISINOS

____

Prof. Cristiano Vasconcellos Ferreira, Dr.
Universidade Federal de Santa Catarina – UFSC – Campus Joinville

____

Prof. Leila Amaral Gontijo, Dra.
Universidade Federal de Santa Catarina – UFSC

____

Prof. Mauricio Uriona Maldonado, Dr.
Universidade Federal de Santa Catarina – UFSC

This thesis is dedicated to Ernesto and Nélia Kubota. Thank you everything.

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“Go ahead, don't let your dreams all behind
Kick all the fears and the threats you will find”

(Almah – Days of the New, 2011)

ABSTRACT

Modularity is a relevant concept in the product development process and brings significant contributions both to the product design, decoupling a complex product into decoupled and less complex modules, and to the manufacturing processes, bringing more autonomous, flexible and loosely coupled production processes. Nevertheless, some aspects regarding its application are not thoroughly clear, e.g. whether modularity in design (MID) leads to modularity in production (MIP), or vice-versa, as well as the technical and managerial implications of those relationships. In addition, one of the sectors that apply modularity extensively is the automotive industry, where modularity has been playing a significant role in substantial transformations. In this sense, this thesis investigates the relationships between MID and MIP in some automotive companies, in order to analyze the conceptual elements that influence the trajectories occurring between those modularity typologies. Firstly, a literature analysis was conducted to (i) identify and analyze automotive projects that explored modularity; (ii) to operationalize MID and MIP concepts and to identify the conceptual elements involved in MID and MIP relationships; and (iii) building and verifying the conceptual framework originated from those relations. Then, a field study, through a multiple cross-case analysis in two passenger cars automakers was carried out, in order to identify if the conceptual elements found in the literature support MID-MIP relationships in the investigated automakers. The findings suggest that MID leads to MIP and MID-MIP relationships have increased compatibility and reduced inconsistencies between product design and manufacturing processes. In addition, MID-MIP relationships occur mostly through suppliers' involvement in design and production phases as well as through outsourcing of engineering and manufacturing activities and product platform strategies. However, MIP application is still limited in one of the companies, because of its manufacturing arrangement characteristics. Further research opportunities suggest deepening some contingencies in modularity application (e.g. global or local suppliers, economic scenario, and the relationships between modularity decisions and company's strategy) and to conduct an ontological study of modularity concepts and definitions.

Keywords: Modularity. Modularity in design. Modularity in production. Automotive sector. Vehicle development.

RESUMO

A modularidade é um conceito relevante no processo de desenvolvimento do produto e traz contribuições significativas tanto para o projeto do produto, decompondo um produto complexo em módulos desacoplados e menos complexos, quanto nos processos de fabricação, tornando os processos de produção mais autônomos, flexíveis e livremente acoplados. No entanto, alguns aspectos relativos à sua aplicação não estão completamente esclarecidos, por exemplo, se a modularidade no projeto leva à modularidade de produção ou vice-versa, bem como as implicações técnicas e gerenciais dessas relações. Além disso, um dos setores que aplicam extensamente a modularidade é o setor automotivo, onde a modularidade vem desempenhando um papel significativo em transformações substanciais. Assim, esta tese investiga as relações entre modularidade de projeto e de produção no setor automotivo brasileiro, a fim de analisar, compreender e explicar os elementos conceituais que influenciam as trajetórias que ocorrem entre esses tipos de modularidade. Para isso, uma análise da literatura foi conduzida para: (i) identificar e analisar projetos automotivos que exploraram a modularidade com mais profundidade; (ii) operacionalizar os conceitos de modularidade de projeto e produção e identificar os elementos conceituais envolvidos nas relações entre modularidade de projeto e produção, e; (iii) construir e verificar o modelo teórico-conceitual oriundo desses conceitos. Em seguida, uma pesquisa de campo, por meio de um estudo de casos múltiplos e cruzados, foi conduzida, visando identificar se os elementos conceituais identificados na literatura suportam as relações entre modularidade de projeto e produção nas montadoras investigadas. Os resultados sugerem que a modularidade de projeto conduz à modularidade de produção e que as relações aumentaram a compatibilidade e reduziram inconsistências entre o projeto e os processos de fabricação dos veículos. Além disso, as relações entre modularidade de projeto e produção ocorrem principalmente por meio do envolvimento dos fornecedores nas fases iniciais de projeto e também da produção, bem como por meio da terceirização das atividades de engenharia e fabricação, e estratégia de plataforma de produtos. No entanto, a aplicação da modularidade de produção ainda é limitada em uma das empresas, devido às suas características estruturais das linhas de produção. Como oportunidades futuras de pesquisa, esta tese sugere aprofundar alguns fatores de contingência na aplicação da modularidade (por exemplo: fornecedores globais ou locais, cenário/contexto econômico e relações entre as decisões de modularidade e a estratégia da empresa) e conduzir um estudo ontológico acerca dos conceitos e definições de modularidade.

Palavras-chave: Modularidade. Modularidade de projeto. Modularidade de produção. Setor Automotivo. Desenvolvimento de veículos.

RESUMO EXPANDIDO

1 INTRODUÇÃO

A modularidade se subdivide em dois tipos principais, conforme o foco de aplicação (BALDWIN; CLARK, 1997; JACOBS et al., 2011; SANCHEZ, 2013; LUCCARELLI et al., 2015): modularidade de projeto (comumente chamada de MID – Modularity in design) e modularidade de produção (MIP – Modularity in production). A MID se refere a estrutura de um produto composta de subsistemas menores que podem ser projetados de forma independente de maneira holística (BALDWIN; CLARK, 1997; RO et al., 2007). Enquanto boa parte da literatura está focada na MID, argumentos similares podem ser utilizados para a MIP (VICKERY et al., 2016). A MIP incorpora a ideia de uma rede dinâmica de módulos de produção relativamente independentes/autônomos que podem ser rapidamente reconfigurados para sustentar e acelerar o lançamento de novos produtos no mercado (JACOBS et al., 2011).

Pesquisas até o presente momento sugerem que a modularidade é relevante para qualquer processo de desenvolvimento de produtos (DANIILIDIS et al., 2011; ULRICH; EPPINGER, 2012) ou de arranjos produtivos (LUCCARELLI et al., 2015). A modularidade sustenta uma estrutura de produto e processo por meio da coordenação eficiente de módulos padronizados e de especificações da interface do módulo (SANCHEZ; MAHONEY, 1996) e a MIP, em particular, mostrou relevância para reduzir o tempo e os custos de desenvolvimento (SIDDIQUE; ROSEN, 1998). No entanto, pesquisas relacionando a MID com a MIP permanecem pouco desenvolvidas em termos de como essas relações podem incrementar benefícios e/ou gerar dificuldades para as montadoras automotivas (CAMPAGNOLO; CAMUFFO, 2010; JACOBS et al. 2011; LUCCARELLI et al., 2015; LUGO-MÁRQUEZ et al., 2016).

A partir desse cenário, emerge a seguinte oportunidade de pesquisa: de que maneiras a modularidade de projeto (MID) e a modularidade de produção (MIP) estão relacionadas entre si, e como essas relações afetam o desenvolvimento de produto e processo em termos de tomadas de decisões e atividades em montadoras que aplicam a modularidade? Assim, esta tese investiga as relações entre MID e MIP para verificar se essas trazem benefícios organizacionais para as empresas que as adotam.

1.1 OBJETIVOS

Identificar e analisar as relações entre MID e MIP no contexto de montadoras de automóveis de passeio, bem como identificar as potencialidades decorrentes dessas relações entre MID e MIP. Para atingir esse objetivo, propõe-se os seguintes objetivos específicos:

- Identificar e analisar as características comuns e particulares dos projetos relevantes de veículos automotores e montadoras em relação à aplicação de modularidade e inovações que esses projetos trazem para a indústria automotiva nacional;
- Identificar da literatura os principais elementos conceituais de modularidade e analisar como estes elementos estabelecem relações entre MID e MIP;
- Verificar as relações entre MID e MIP e como essas podem gerar benefícios e/ou limitações em termos das decisões organizacionais e técnicas dos fabricantes de automóveis.

2 MÉTODOS DE PESQUISA

Este capítulo se subdivide em duas partes. Na primeira, apresenta-se aspectos gerais relacionados as decisões metodológicas realizadas, para em seguida descrever os procedimentos conduzidos na fase teórica da pesquisa. Posteriormente, descreve-se as etapas elaboradas para a condução da fase empírica desta tese.

2.1 PROCEDIMENTOS DE COLETA E ANÁLISE DOS DADOS – FASE TEÓRICA

Os procedimentos metodológicos foram determinados considerando a natureza do objetivo deste trabalho e o referencial teórico acerca das relações entre MID e MIP no setor automotivo. Pouco se sabe sobre as implicações da arquitetura do produto no design organizacional, tanto dentro da empresa como em toda a cadeia de suprimentos, considerando-se um contexto de mudanças em direção a uma arquitetura de produto mais modular (RO et al., 2007; JACOBS et al., 2011; LUCCARELLI et al., 2015). Tal panorama sugere a demanda por mais pesquisas sobre modularidade nesse segmento industrial.

Desse modo, na etapa de análise da literatura, buscou-se artigos que evidenciavam a aplicação da modularidade de um modo geral, para em seguida filtrar aqueles que abordavam o setor automotivo.

Posteriormente, selecionou-se os artigos que explicitavam a aplicação da MID e da MIP. Esses trabalhos focaram principalmente o impacto do MID e MIP em aspectos como desempenho da empresa, integração de desempenho, integração da cadeia de suprimentos e gerenciamento de produtos complexos.

O portfólio final de artigos que abordavam a modularidade de projeto e de produção no setor automotivo, sugerindo possíveis relações entre essas duas tipologias, consistiu de 61 artigos, de onde foram identificados os principais elementos conceituais relacionados à modularidade. A análise dos trabalhos iniciou-se por meio de uma leitura inspecional (ADLER; VAN DOREN, 1972) focada em (i) encontrar os principais conceitos e definições sobre modularidade nos trabalhos analisados e; (ii) identificar os principais conceitos e elementos que emergiram nessas definições. Após a leitura de inspeção, a leitura analítica foi conduzida, seguindo a lógica da análise de conteúdo proposta por Bardin (1977), dividida em: Organização da análise, esta primeira etapa consistiu em organizar os 61 artigos relacionados a MID e MIP no setor automotivo para sustentar a interpretação final dos dados; Codificação dos dados, visando transformar os conteúdos obtidos em dados mais precisos para a classificação seguindo os conceitos principais e os autores que apoiam cada evidência; Categorização, que consistiu em classificar documentos e informações de um conjunto de dados para diferenciação e reagrupamento, e; Inferência, que se refere à análise das causas que levaram aos efeitos.

Assim, ao final desta etapa, propôs-se um modelo teórico-conceitual acerca da relação entre MID e MIP, que identificou e analisou como os elementos conceituais encontrados influenciam e/ou afetam a conexão existente entre a MID e a MIP.

2.2 PROCEDIMENTOS DE COLETA E ANÁLISE DOS DADOS – FASE EMPÍRICA

Após a análise da literatura e posterior elaboração do modelo conceitual, partiu-se para a fase empírica da pesquisa, visando verificar e demonstrar a aplicabilidade do modelo conceitual das relações entre MID e MIP no setor automotivo. Para isso, definiu-se a abordagem de estudo de caso como método de investigação, pois essa abordagem é apropriada para pesquisas que demandam mais aprofundamento de determinado tema, bem como para trabalhos que possuam questões de pesquisa incorporando elementos explanatórios (VOSS, 2009; YIN, 2014). Para a seleção das empresas a serem investigadas, utilizou-se critérios de seleção objetivos, conforme recomendado por Sousa e Voss (2001). Nesse sentido, as principais razões para a seleção das montadoras investigadas foram: (i) O fato de as empresas terem relativa autonomia para desenvolver projetos locais; (ii) possuir engenheiros, gestores e/ou diretores que estiveram envolvidos nas fases iniciais do processo de desenvolvimento de produtos; (iii) ter fornecedores modulistas para desenvolver módulos e/ou componentes; (iv) possuir cerca de 10 anos de experiência na aplicação da modularidade, e; (v) Permitir acesso aos dados para coleta.

Para a coleta de dados, buscou-se selecionar entrevistados que estiveram envolvidos de forma mais aproximada com as atividades e processos e relacionados a aplicação da modularidade (conforme recomendado por BARDIN, 1977). Assim, foram entrevistados executivos e engenheiros, envolvidos com o projeto de produto e as decisões estratégicas relacionadas às plataformas de produto da montadora. Na primeira montadora analisada, os selecionados para serem entrevistados foram o gerente do departamento de plataformas e sistemas, o diretor do departamento de engenharia de projetos e um engenheiro de projetos, que também estava envolvido com a estruturação e adequação das linhas de manufatura aos projetos modulares.

Na segunda montadora, os selecionados foram o gerente de desenvolvimento de produtos, o gerente de pesquisa e desenvolvimento e o gestor da área de simulação e elementos finitos. Cada entrevista durou cerca de uma hora e meia e os dados foram registrados por meio de anotações em papel, uma vez que a empresa não permitiu a utilização de gravação em áudio.

Posteriormente, questões adicionais foram enviadas por e-mail e feitas por telefone aos entrevistados, para esclarecer algumas dúvidas sobre os dados e também para buscar respostas de outras questões emergentes durante a análise. Além disso, dados secundários tais como informações do website da empresa e informações sobre a nova plataforma de produtos da mesma foram coletados e posteriormente considerados na análise.

Assim, extraiu-se, a partir das entrevistas, os principais elementos conceituais envolvidos nas relações entre MID e MIP. Conduziu-se essa análise de conteúdo seguindo as orientações de Bardin (1977), Miles e Huberman (2014), e Yin (2014), de forma combinada: organização dos dados, codificação e categorização dos dados, identificação de inter-relações entre constructos, e posterior inferência a partir dos resultados encontrados. A próxima seção apresenta os resultados e as contribuições decorrentes desta tese de doutorado.

3 RESULTADOS E DISCUSSÃO

Esta seção apresenta os resultados encontrados nesta tese, subdividindo-se entre o desenvolvimento e apresentação do modelo conceitual e as contribuições decorrentes do mesmo.

3.1 DESENVOLVIMENTO E VERIFICAÇÃO DO MODELO CONCEITUAL

A partir da análise da literatura sobre modularidade, desenvolveu-se o presente modelo conceitual que estrutura as relações entre a MID e a MIP. Inicialmente, identificou-se os principais elementos conceituais oriundos da literatura sobre MID e MIP:

- Terceirização (outsourcing), que envolve a transferência de atividades de engenharia e montagem dos módulos/componentes da montadora para os fornecedores;
- Padronização (standardization), que possibilita recombinar componentes de produtos/veículos distintos sem uma elaboração muito complexa de interfaces;
- Variedade de produtos (product variety), que consiste na oferta de diversidade de produtos a partir de uma plataforma de produto;
- Funcionalidade (functionality), que se refere a capacidade ou capacidade de executar uma tarefa ou função. Módulos de um produto podem executar uma ou mais funcionalidades de acordo com o design do produto;
- "Comunalidade" (commonality) que se refere ao nível de módulos/componentes comuns a diferentes produtos. Compartilhar partes comuns contribui para relações entre MID e MIP;
- Interdependência entre módulos (interdependence between modules), que envolve o grau de independência estrutural que os módulos/componentes têm entre si;
- Co-design com fornecedores (co-design with suppliers), que trata do grau de envolvimento dos fornecedores no desenvolvimento de produtos, e;
- Plataforma de produto (product platform), que consiste em uma estratégia central para as empresas para lidar com fabricação ágil e desenvolvimento de novos produtos, que incorporam várias abordagens.

Em seguida, verificou-se o modelo conceitual em duas montadoras automotivas. A primeira verificação, feita na Montadora A (assim denominada por motivos de sigilo). Na Montadora A, funcionalidade e a interdependência entre os módulos são influentes na relação entre MID e MIP. As decisões de funcionalidade são exploradas durante a aplicação da MID. Por meio dessas decisões, a Montadora A é capaz de definir as interdependências dos módulos. Então, após estabelecer todas as funções e interdependências, constrói-se os módulos e os componentes que serão comuns a uma certa variedade de veículos. O estabelecimento de funcionalidades e suas respectivas interdependências possibilitam a construção de módulos e interfaces padronizados e comuns, que permitem decisões sobre quais e quantos módulos serão compartilhados entre a plataforma de produtos da Montadora A.

No entanto, apesar das funcionalidades e das decisões de interdependência dos módulos, de fato, algumas mudanças ocorreram em relação às mudanças nos processos de fabricação. As principais modificações identificadas na Montadora A foram: (i) maior automação nos processos; (ii) divisão de produção em módulos de processo manual e automatizado e; (iii) evitar operadores isolados nas linhas de produção. Foram mudanças incrementais devido ao nível de investimento que a empresa tinha disponível. Essencialmente, os investimentos foram focados em elevar suas capacidades produtivas, substituir equipamentos e modificar a tecnologia. Nesse sentido, o fabricante de automóveis não modificou radicalmente seus processos de fabricação.

Outros elementos conceituais que sofreram poucas mudanças envolvem a perspectiva de relacionamento entre fabricantes de automóveis e fornecedores. Em termos de terceirização e co-design com fornecedores, a Montadora A não enfrentou mudanças substanciais. O projeto dos módulos foi uma atividade transferida para fornecedores, mas ainda centralizada sob os requisitos de qualidade da montadora. Os fornecedores criam todo o projeto do módulo e se tornam especialistas nessa matéria, enquanto a montadora analisa se o módulo funcionará adequadamente na arquitetura do produto.

Nas decisões de variedades de produtos, a empresa analisa as demandas do mercado antes de construir todas as variantes necessárias de acordo com os pedidos dos clientes. Ou seja, a variedade de produtos não é um elemento conceitual intrinsecamente ligado a modularidade. O mercado exige mais ou menos variedade, por isso é possível levar essas informações em consideração posteriormente.

Posteriormente, também se verificou a aplicação do modelo na Montadora B. Nessa montadora, as relações entre MID e MIP são exploradas por meio da terceirização e co-design com conceitos de fornecedores, e a trajetória de relacionamento é de MID para MIP pela seleção de fornecedores de primeiro nível, com alguns recursos que levam de MIP para MID. Conforme a sua competência, os fornecedores decidem os componentes que irão compor o módulo ou até mesmo propõem alguns requisitos de qualidade e critérios de construção, o que permite maior autonomia por parte dos fornecedores. Esses, por sua vez, tornam-se responsáveis pela construção de seus respectivos módulos, uma vez que a Montadora B transfere os processos de fabricação dos módulos para os fornecedores. Na perspectiva da MIP, o conceito modular da planta orientou algumas especificações de montagem e sequenciamento pré-montagem, bem como layout de fabricação e os termos contratuais de alguns fornecedores.

Em termos de projeto de produto modular, a Montadora B define conceitos comuns e de normalização em termos de decisão e seleção de quais componentes e módulos serão compartilhados com uma variedade particular de veículos e marcas derivadas da plataforma do produto. O fabricante de automóveis aplica esses conceitos visando maior compartilhamento de componentes e, portanto, reduz os custos individuais ao comprar esses componentes. É uma decisão tomada durante a fase de projeto. Os conceitos de comunalidade e padronização estão ligados aos conceitos relacionados aos fornecedores (terceirização e co-design).

Ainda, a Montadora B explora esses conceitos negociando módulos e componentes com fornecedores exclusivos. A montadora considera os fornecedores globais para aumentar os módulos comuns, pois assim é possível gerar mais economias de escala e contribuir para processos de produção mais padronizados, além de reduzir as mudanças por causa de menos modificações no projeto do produto. Além disso, durante o projeto modular, a empresa se concentrou em processos produtivos comuns para construir as diversas variantes modulares por meio de um desenvolvimento conceitual em termos de ciclo de vida do produto, reduzindo a complexidade de produto e os custos.

No entanto, tais decisões podem trazer algumas desvantagens. Considerando que certos módulos e componentes estão sob a responsabilidade de fornecedores únicos, problemas de qualidade e/ou questões comerciais podem gerar problemas técnicos e organizacionais significativos, afetando negativamente um maior volume de produtos, com menor possibilidade de superar os problemas devido à exclusividade dos fornecedores, limitando uma resposta mais ágil diante de eventuais contratempos.

A relação entre MID e MIP pode ser importante no nível estratégico. Inicialmente, a Montadora B enfrentou dificuldades, pois a plataforma de produtos planejada mudou com o desenvolvimento de veículos novos, o que causou um impacto na produção em termos de aumento de investimento para mais flexibilidade de produção e interdependência. Entretanto, a empresa poderá, futuramente, evitar a perda de investimentos passados ou minimizar essas perdas por meio de um planejamento do projeto de produtos modulares com um ciclo de vida mais longo. Assim, os novos produtos introduzidos no mercado podem ser fabricados com um processo de produção mais padronizado que demandarão menos mudanças, uma vez que os processos de fabricação e montagem dos veículos projetados serão pensados, de forma antecipada, para atender as atuais e futuras variações da plataforma de produtos modulares.

Adicionalmente, as decisões sobre o grau de variedade de produtos são definidas com base no mercado e são tratadas no planejamento estratégico da empresa. Isso também pode servir como informação relevante para o desenvolvimento de módulos que possam atender a mais variantes dos veículos projetados.

3.2 DISCUSSÃO E CONTRIBUIÇÕES

Inicialmente, esta tese verificou que o modelo conceitual desenvolvido tem como principal contribuição uma demonstração sistemática dos elementos conceituais primários que estão envolvidos na aplicação da modularidade em montadoras automotivas. Esses constructos que formam o modelo conceitual foram previamente identificados na literatura, no entanto são explorados isoladamente ou apenas parcialmente em conjunto. Assim, esta tese contribui para a identificação e análise dos principais conceitos que sustentam as relações entre MID e MIP, permitindo aprimorar a arquitetura de produto e a produção modular. Além disso, a identificação e organização desses conceitos pode ser importante para auxiliar acadêmicos, engenheiros e gestores a examinar como os principais elementos conceituais afetam as decisões acerca da modularidade em outras empresas que adotam estratégias modulares em seus produtos e processos.

Adicionalmente, o modelo conceitual desenvolvido nesta tese tem a flexibilidade de ser aplicada conforme as demandas das montadoras, tanto para a modularização de novos produtos como para o redesenho de produtos (à luz da estratégia modular). Assim, de acordo com os objetivos da empresa em relação à aplicação da modularidade, o modelo pode ser ajustado para ser implementado de modo a atender as necessidades da organização. Esse modelo integra o projeto do produto e seus respectivos processos de fabricação por meio da modularidade. Ainda, o modelo conceitual também contribui para compreender como a MID pode viabilizar a MIP (e vice-versa) para se alcançar uma melhor sincronização entre a arquitetura do produto e os processos de fabricação.

Os estudos de caso realizados neste estudo reforçaram a aplicabilidade do modelo conceitual, o qual pode ser útil para o redesenho de funções, de estruturas e aprimoramento do gerenciamento do projeto modular. O desenvolvimento e a verificação do modelo conceitual revelaram que tanto a literatura como a prática exploram a MID mais do que a MIP, e que as montadoras realizam suas principais decisões durante as atividades da MID, antes das definições de MIP. Ou seja, tais decisões afetarão o desenvolvimento posterior da MIP. Assim, a tese demonstra que a MID normalmente orienta as decisões relacionadas a MIP por meio das construções acima mencionadas.

Ainda, acrescenta-se que as empresas interessadas em desenvolver novos produtos modulares também podem considerar o uso do modelo conceitual desenvolvido nesta tese para facilitar a definição de seus requisitos de produção e projeto de produtos. Tais aplicações podem orientar gerentes e especialistas no planejamento do projeto modular, levando em consideração seus impactos técnicos e organizacionais sobre as capacidades de produção modular (ou vice-versa). A próxima seção apresenta as principais conclusões extraídas desta tese.

4 CONCLUSÕES

Esta seção apresenta os principais pontos conclusivos extraídos a partir desta tese, bem como as contribuições decorrentes do desenvolvimento da pesquisa e as limitações e oportunidades futuras identificadas. Desse modo, esta seção está subdividida em: (i) principais pontos conclusivos e; (ii) limitações e oportunidades futuras de pesquisa.

4.1 PRINCIPAIS PONTOS CONCLUSIVOS

A partir do desenvolvimento desta tese, pode-se concluir que as vantagens da modularidade ainda são mais expostas do que as dificuldades, e a fase empírica desta pesquisa corrobora esses resultados teóricos, ressaltando que os benefícios da modularidade foram mais externados do que as desvantagens, e também que as montadoras absorvem mais desses benefícios do que os fornecedores. Ainda, embora a literatura aponte para um relacionamento crescente com os fornecedores, o estudo de campo mostra que as montadoras ainda centralizam a maioria das decisões em relação a MID, o que significa que ainda há um processo consideravelmente verticalizado em termos de decisões de modularidade em algumas empresas automotivas e suas respectivas cadeias de suprimentos. Assim, evidencia-se que os fornecedores têm menos autonomia do que parte da literatura vigente em modularidade sugere.

Além disso, ao contrário do que a literatura recente sobre modularidade sugere, os estudos de caso demonstram que a variedade de produtos é desenvolvida previamente às definições de modularidade no projeto. Isso indica que, na realidade, a modularidade de projeto atua para atender às demandas por maior variedade de produtos ao invés de definir essas variantes (que já advém de pesquisas de mercado).

Adicionalmente, verificou-se por meio dos exemplos automotivos examinados e os estudos de caso que algumas empresas não conseguem obter os máximos benefícios da modularidade porque planejam a MID sem considerar as implicações técnicas e organizacionais posteriores dentro dos processos de produção. Assim, esta tese argumenta que a análise de conceitos e objetivos de modularidade para estabelecer as relações entre MID e MIP podem ser relevantes para maior absorção das vantagens da modularidade. As montadoras investigadas alinharam suas definições de projeto modular aos processos produtivos, apesar de terem realizados ajustes limitados em termos do conceito de MIP. No entanto, mesmo com esses ajustes limitados em MIP, foi possível planejar a MID considerando novas implicações nos processos de fabricação (e vice-versa). Portanto, esta tese afirma que as relações entre MID e MIP de fato melhoraram a compatibilidade entre os módulos da plataforma do produto e os processos de fabricação e montagem dos veículos, reduzindo o risco de inconsistências e melhorando a sincronização entre o projeto e a produção modular.

4.2 LIMITAÇÕES E OPORTUNIDADES DE PESQUISAS FUTURAS

Esta tese tem algumas limitações. Primeiramente, sob a ótica metodológica, apenas dois estudos de caso foram realizados, o que poderia limitar a validade externa do trabalho. No entanto, a investigação empírica foi suficiente para sugerir implicações teóricas e evidenciar alguns impactos gerenciais. Isso porque o estudo de campo coletou múltiplas fontes de evidência de ambas as empresas, incrementando a validade interna e do construto deste trabalho.

Além disso, a tese identificou oportunidades promissoras, sendo uma das principais a proposição de que certas contingências afetem relações MID-MIP. Fatores como capacidades de produção, seleção de fornecedores locais e/ou globais e nível de descentralização no processo de desenvolvimento do produto parecem influenciar as relações MID-MIP. Essas contingências surgiram durante os estudos de caso. No entanto, essas não foram profundamente analisadas em termos de como podem afetar decisões relacionadas a implementação da modularidade. Assim, pesquisas futuras podem investigar as contingências envolvidas na aplicação da MID e MIP em montadoras automotivas.

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LIST OF ACRONYMS

ANFAVEA – Associação Nacional dos Fabricantes de Veículos Automotores
BRIC – Brazil, Russia, India and China (emerging economies)
CAPES – Coordination of Superior Level Staff Improvement
CMF – Common Module Family
CNPq – Brazilian National Council for Scientific Development
EurOMA – European Operations Management Association
FENABRAVE – Federação Nacional da Distribuição de Veículos Automotores
GDP – Gross Domestic Product
GM – General Motors
IJAMT – International Journal of Advanced Manufacturing Technology
IJPE – International Journal of Production Economics
MID – Modularity in design
MIP – Modularity in production
MIU – Modularity in use
MQB – Modularer Querbaukasten
NPD – New Product Development
OEM – Original Equipment Manufacturer
R&D – Research and Development
SciELO – Scientific Electronic Library Online
TNC – Transnational companies
VW – Volkswagen

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1 INTRODUCTION

In areas of intense competitiveness, differentiated features of product architecture may contribute to better economic results and company market share. The architecture of a product describes the scheme by which the product's functional elements are arranged into major physical building blocks and how these building blocks interact. In turn, the degree to which functional elements are assigned to building blocks determines the degree to which the product architecture is modular (VICKERY et al., 2015). Modularity is considered to be one of the most important features of product architecture (ULRICH; EPPINGER, 2012) and is commonly known as a way of organizing the architecture of a product through interacting parts (HUANG; KUSIAK, 1998). In fact, the term “modularity” has been used to describe the use of common units to create product variants by changing only specific product modules on a basic platform (HUANG; KUSIAK, 1998), thus facilitating complexity management (ETHIRAJ; LEVINTHAL, 2004; 2008).

Modular architectures allow products to be adjusted to different markets, with some modules working as variant modules on a basic platform (LUGO-MÁRQUEZ et al., 2016). Additionally, depending on the products that a company launches in a market, the company should have the option to make changes to its manufacturing processes and/or plant distribution. In most of the engineering industry, the design and preparation of process assembly take place across different departments, with non-overlapping personnel (LUGO-MÁRQUEZ et al., 2016). Thus, modularity can also affect the organization of the manufacturing process by enhancing flexibility, reducing operational costs, and minimizing complexity through the establishment of independent and autonomous processes (JACOBS et al., 2011; LUCARELLI et al., 2015).

There are two main types of modularity, according to the focus of the application (BALDWIN; CLARK, 1997; JACOBS et al., 2011; SANCHEZ, 2013; LUCARELLI et al., 2015): modularity in design (MID) and modularity in production (MIP). MID refers to the structure of a product composed of smaller subsystems that can be designed in an independent way with a holistic view (BALDWIN; CLARK, 1997; RO et al., 2007). In this sense, modular design can benefit products through autonomous and modular innovation (ETHIRAJ; LEVINTHAL, 2004). However, while most of the literature on modularity has focused on MID, similar arguments can be used for the application of MIP (VICKERY et al., 2016). MIP embodies the notion of a dynamic network of relatively autonomous/independent production modules that can be easily and rapidly reconfigured to support and accelerate the launch of a new product (JACOBS et al., 2011). It is important to emphasize that the literature addressing MIP is less developed than that addressing MID (JACOBS et al., 2011).

The research to date suggests that the application of modularity is relevant to any product development process (DANIILIDIS et al., 2011; ULRICH; EPPINGER, 2012) or production arrangement (LUCARELLI et al., 2015). Modularity supports a loosely coupled product and process structure through the efficient coordination of standardized modules and module interface specifications (SANCHEZ; MAHONEY, 1996), and MIP, in particular, has been shown to be valuable for reducing development time and costs (SIDDIQUE; ROSEN, 1998). However, some research areas within this field remain undeveloped (LUCARELLI et al., 2015; LUGO-MÁRQUEZ et al., 2016), and one of these concerns the relationship between MID and MIP (CAMPAGNOLO; CAMUFFO, 2010; JACOBS et al. 2011). Indeed, both MID and MIP are approaches that could address the challenges associated with rapidly changing technologies, clockspeed product development cycles, and sophisticated customer demands (VICKERY et al., 2016).

Previous studies have illustrated the importance of the MID-MIP relationship (e.g. SCHILLING; STEENSMA, 2001; BRUSONI; PRENCIPE, 2001; CAMPAGNOLO; CAMUFFO, 2009; JACOBS et al., 2011; LUCARELLI et al., 2015; LUGO-MÁRQUEZ et al., 2016). However, a limited number of studies investigate how MID and MIP are organized, the extent to which it is possible to establish relationships between them, and their benefits and drawbacks in the product development process (e.g. CAMPAGNOLO; CAMUFFO, 2010; JACOBS et al., 2011; LUGO-MÁRQUEZ et al., 2016). These relationships are relevant because, through their analysis, it is possible to see a company’s level of maturity in applying the concept of modularity (SANCHEZ, 2013). Thus, there is a need for more research and applications exploring how and why to configure design activities and tasks connected to production arrangements and decisions (CAMPAGNOLO; CAMUFFO, 2010; LUCARELLI et al., 2015).

In terms of MID-MIP relationships themselves, MIP appears to be an inevitable result of higher product modularity (BRUSONI; PRENCIPE, 2001; JACOBS et al., 2011), with the modular product architecture conditioning the modular production processes. On the other hand, some examples suggest that the concept of modularity can be deployed in production without the product being designed in modules (RODRIGUES et al., 2012). In other situations, it is unclear whether product modularity determines outsourcing or outsourcing activities tasks affect product modularity (CAMPAGNOLO; CAMUFFO, 2009). A certain type of product architecture (including a new product development process) is conditioned by the organizational capabilities of a given company and is strongly influenced by the evolution of economic and cultural characteristics, as well as the historical trajectory of the country in which the company is established (FUJIMOTO, 2008). In some situations, modularity may improve both design and assembly process efficiency (LUGO-MÁRQUEZ et al., 2016). However, there are also situations in which modularity fails to bring the expected benefits for outsourcing activities and design phases (ZIRPOLI; BECKER, 2011b).

On other occasions, it seems that an autonomous and independent modular production structure might affect the quality of a modular product/platform architecture (VICKERY et al., 2016). In this context, MID is conditioned by the potentialities and limitations of the manufacturing process organization, resulting in a scenario in which MIP influences MID decisions. Consequently, changes in the hierarchies of production systems and/or inter-firm systems cause tension in their relationships with product architecture, thus encouraging the redefinition of the product architecture (TAKEISHI; FUJIMOTO, 2003). To support this MIP-to-MID trajectory and achieve changes in product requirements, MIP needs to be standardized to facilitate process redesign and/or extended through the addition of new and agile modules (MIKKOLA, 2006). To accomplish their design and production objectives, automotive companies have been pursuing various strategies to improve their product and process quality, including modularity in products and in manufacturing processes (LUCARELLI et al., 2015; JACOBS et al., 2011).

However, previous studies on modularity show contradictory evidence regarding applications of modularity in the automotive industry (CABIGIOSU et al., 2013). These contrasts occur because auto industries, in different areas, normally follow different ways of implementing modularization. Such situation results in a variety of product architectures, production processes hierarchies, and boundaries (TAKEISHI; FUJIMOTO, 2001). Overall, the modularity concept may be a feasible alternative for car manufacturers because it may facilitate the creation of product variants through changes in product architectures and offer a variety of future opportunities for both MID and MIP designers, manufacturers, and buyers (LUCARELLI et al., 2015). From this scenario, the following research question emerged: In what ways are Modularity in Design (MID) and Modularity in Production (MIP) related to one another, and how do these relationships affect product and process development activities and decisions in car manufacturers that apply modularity?

Thus, this thesis investigates the relationships between MID and MIP in order to verify whether their relationships bring managerial benefits to the companies that adopt them, as depicted by the objectives in the next section.

1.1 THESIS OBJECTIVES

As earlier presented, the research question for this study was developed from the literature analysis. The main objective of this doctoral thesis is to identify and analyze the relationships between MID and MIP in the context of passenger car manufacturers, as well as to identify possibilities for establishing MID–MIP relations. To achieve this objective, this thesis proposes the following specific objectives (SOs):

- SO1: Identify and analyze the common and particular characteristics of the relevant automotive vehicle projects and automakers regarding the application of modularity and innovations that these projects bring to the national automotive industry;
- SO2: Identify from the literature the main conceptual elements of modularity and analyze how these elements establish relationships between MID and MIP;
- SO3: Verify the relationships between MID and MIP and how these can generate benefits and/or limitations in terms of the organizational and technical decisions of car manufacturers.

By accomplishing each specific objective, this thesis aims to fulfill both the main objective and, consequently, the research question. The importance of conducting this thesis as well as the theoretical and managerial contributions are presented in the next section.

1.2 THESIS RELEVANCE

Through modularity, companies can increase flexibility in their design and production decisions. To facilitate flexibility in organization and business, modular product design is essential, beginning with the conception of the product and the layout of the production plant (TAKEISHI; FUJIMOTO, 2003; LUGO-MÁRQUEZ et al., 2016). In the case of product redesign (which, as its name suggests, begins from an existing product), modular redesign facilitates improvements in the layout of a plant that is already operating, thus reducing assembly and manufacturing times and increasing flexibility to support the development of a great variety of products at lower costs and with shorter delivery times (GUPTA, 2013). Consequently, it is possible to generate positive changes in plant layout, thereby facilitating the organization of manufacturing processes and increasing flexibility and production levels using modular concepts in both design and production (DEKKERS et al., 2013; SAGHIRI; BARNES, 2016). It can be argued, therefore, that modularity can support the integrated design of interfaces, physical modules, and their respective manufacturing production. As previously mentioned, there are considerable conflicts involved in product and process development, and one of the biggest challenges concerns the inconsistency created between MID and MIP (SALVADOR et al., 2002; PANDREMENOS et al., 2009; NEPAL et al., 2012; MACDUFFIE, 2013; KAMRAD et al., 2013). However, although MID–MIP relationships may play an important role in reducing product and process issues, they are more difficult to implement than the literature suggests (PERSSON; AHLSTRÖM, 2006).

In some cases, production conditions and capabilities might affect MID decisions (TAKEISHI; FUJIMOTO, 2003) or even prevent them from having a significant impact on product design (RODRIGUES et al., 2012). In other situations, modular design decisions may fail to influence modular production settings. Yet, the trajectory of an MID–MIP relationship can be a two-way street: either MID can lead to MIP or MIP can lead to MID (TAKEISHI; FUJIMOTO, 2003). This can occur due to internal and external factors influencing the considered unit of analysis (RO et al., 2007; CABIGIOSU et al., 2013). Yet, although the relationship between modularity and the ability to outsource is explicit (CABIGIOSU et al., 2013), it is still unclear whether modularity decisions lead to outsourcing activities or whether outsourcing decisions define modularity (CAMPAGNOLO; CAMUFFO, 2009). In this sense, the relationships between MID and MIP can be important for establishing better decisions in terms of managing modules' outsourcing and transferring responsibilities to suppliers.

Some studies have shown that relationships between MID and MIP may have positive impacts on design and assembly efficiency (e.g. JACOBS et al., 2011; LUCARELLI et al., 2015; LUGO-MÁRQUEZ et al., 2016). However, as pointed out by Bonvoisin et al. (2016) and Jacobs et al. (2011), in terms of results obtained through modularity, concrete and/or empirical evidence is rarely provided, and potential benefits are not always supported by evidence. Thus, more studies are needed to generate systematic and solid evidence of the advantages and drawbacks of MID and MIP and their relations (JACOBS et al., 2011; LUCARELLI et al., 2015; BONVOISIN et al., 2016). Studies focused on the consequences of modularization are not in-depth in the sense of presenting possible approaches for the adequate implementation or generation of modularization strategies (PIRAN et al., 2015). Further efforts in this direction would provide relevant contributions, such as a deeper understanding of modularity from the functional, life cycle, and mixed perspectives (CAMPAGNOLO; CAMUFFO, 2010); information on the decision between internal and outsourced modules (SAKO; MURRAY, 1999; PANDREMENOS et al., 2009); and a more detailed exploration of product and organizational architecture (HOETKER, 2006; KUMAR; CHATTERJEE, 2013). In addition, there is a need for coordination when designing modular products and processes simultaneously (PERSSON; ALHSTRÖM 2006). Those subjects involve, to some extent, the relationships between MID and MIP.

In the automotive industry, modularity has been applied from both the product and the process perspective. For instance, Fiat Tipo's design and assembly employed a number of pre-assembled modules (namely, for a cockpit and a door), the majority of which were internally designed, manufactured, and assembled (PANDREMENOS et al., 2009). Volkswagen's *Modularer Querbaukasten* (MQB) allows modularization in manufacturing by underpinning almost all transverse-engine Volkswagen group models (LUCARELLI et al., 2015). However, although there are many successful examples of modularity adoption in the literature, complete modularity integration has not yet become standard in the automotive industry (PANDREMENOS et al., 2009). This may be due to the comparatively limited understanding of what modular strategies really mean and of the organizational changes necessary to implement modularity strategies effectively (SANCHEZ, 2013). In this sense, MID–MIP relationships are a relevant approach to reducing the risks of technical incompatibility and minimizing costs through assembly and quality (PARALIKAS et al., 2011; PANDREMENOS et al., 2009), issues that stem from the inherent complexity of vehicle architectures.

Modularity strategies and the relationships between MID and MIP can be feasible options for automotive manufacturers, since such relations may offer significant future opportunities for designers, manufacturers, and buyers due to their capacity to support vehicle manufacturers in the application of distinct and interchangeable technologies involving both production processes and products (CAMPAGNOLO; CAMUFFO, 2010; LUCARELLI et al., 2015). In addition, investigating the relationships between MID and MIP can be important for addressing the diversity of stakeholders requirements and interests, since, to capture the full benefits of modularity, different participants and their respective requirements must be taken into account (PERSSON; AHLSTRÖM, 2006).

Thus, it becomes important to investigate ways to establish integrative and robust relationships between MID and MIP (CAMPAGNOLO; CAMUFFO, 2010) to improve the foundations of decision-making in the car development process. Identifying the decisions involving MID and MIP relations in automotive companies will contribute to establishing why and how car manufacturers can improve their processes in order to build all necessary module variants with more agility (PARALIKAS et al., 2011). Considering this scenario, this thesis takes up the challenge of exploring the main drivers, concepts, benefits, and drawbacks of MID–MIP relationships. In so doing, this thesis seeks to contribute to a better application of modularity in both design and production. The next section presents the structure of the thesis.

1.3 STRUCTURE OF THE THESIS

This thesis was developed following Resolution 002/2015 (UFSC, 2015) of the Post-Graduate Program of Production Engineering of the Federal University of Santa Catarina (Universidade Federal de Santa Catarina). This means that it is an article-based thesis that complies with the requirements of this resolution. All articles presented here are part of the candidate's research project and are accompanied by copyrights permissions or documents stating that the relevant conference papers are not copyrighted. Appendix A (at the end of this thesis) presents the first page of each article in this thesis. Appendix B lists the contributions of this thesis. Appendix C presents the permissions for using the articles on this thesis.

Following this introduction, which has presented the objectives of this thesis, Chapter 2 describes the research methods and procedures. It also presents the decisions related to the thesis' development stages and how these steps are connected to each other. Additionally, it presents the rationale and criteria for selecting automotive companies and, particularly, passenger cars as the object of analysis. Chapter 2 ends by presenting the decisions regarding the data collection and analysis procedures for each stage of the literature review and analysis, as well as the procedures to conduct the field study stage. Each step of the research design culminates in a research article as a contribution. This chapter also outlines the relations among the articles comprising this thesis and discusses how each article contributes to the others and to the thesis as a whole.

Chapter 3 identifies and analyzes the common and particular characteristics of five vehicle projects in the Brazilian automotive market (contents of the first article[1]). It reviews the literature on the product development process in the Brazilian automotive industry and identifies several similarities, such as locally commanded design activities, research and development (R&D) centers focused on the local market, and the application of modularity in design and processes. In the context of particular features, a distinct focus on the modularity employed in each vehicle emerged. Chapter 5 concludes by highlighting important criteria for selecting the car manufacturers to be contacted for the empirical investigation and by discussing preliminary attempts to connect MID and MIP.

Chapter 4 reviews the concepts and definitions of modularity (contents of the second article[2]) in order to build definitions for MID and MIP that facilitate an analysis of their relationships. Additionally, it discusses the literature on other modularity typologies, such as modularity-in-use (MIU), organizational modularity, and service modularity. It shows that MID and MIP are the most commonly applied modularity typologies and that the automotive industry is one of the economic sectors that have been increasingly adopting modularity. The chapter discusses the rationale for exploring the literature on MID application in the automotive industry (Chapter 4), as well as the benefits and drawbacks of MID. It also provides a foundation from which to analyze how modularity emerged as an important research subject by focusing on several vehicle projects characterized by the adoption of MID and MIP concepts in their product design and production decisions (Chapter 5).

Chapter 5 analyzes the literature on the main benefits, drawbacks, and recommendations of modularity when applied in automotive companies (contents of the third article[3]). The analysis considers both the

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[1] KUBOTA, F.I.; CAUCHICK MIGUEL, P.A. Identification and analysis of characteristics of development of vehicles in the Brazilian automotive industry. Proceedings of the 21st Gerpisa International Colloquium, Paris, France. 2013.

[2] CORRÊA, L.A.; KUBOTA, F.I.; CAUCHICK MIGUEL, P.A. Towards a contribution to modularity concepts and principal domains. Product: Management & Development, v. 10, n. 2, p. 119-130, 2012.

[3] KUBOTA, F.I.; GONTIJO, L.A.; CAUCHICK MIGUEL, P.A. Design modularity: identification of benefits and difficulties through a bibliographical

automakers (OEMs) and the suppliers' perspectives on the application of modularity. Through a systematic literature review of articles focused on modularity in the automotive industry, the chapter narrows down the analysis of modularity's main research gaps. It suggests that automakers usually acquire more benefits than suppliers do when applying modularity, while the suppliers face more challenges and changes in their design and production activities. Additionally, Chapter 4 points to the relationships between MID and MIP as a promising topic for further investigation.

Chapter 6 presents the preliminary building of the theoretical–conceptual framework of MID–MIP relationships (contents of the fourth article[4]). At this stage, the systematic literature review focuses on the conceptual elements that emerged as part of the application of modularity in automotive companies. In this sense, concepts like co-design (with suppliers), commonality, standardization, interdependence between modules, outsourcing, and product platforms were identified as influencing MID-MIP decisions. However, this preliminary framework had limitations regarding the trajectories and specific concepts connecting MID and MIP.

Chapter 7 deepens the review and analysis of MID–MIP relationships (contents of the fifth article[5]), resulting in a final conceptual framework that establishes with more robustness how MID and MIP are related. This chapter culminates in a theoretical analysis of the connections between MID and MIP by discussing relevant modularity concepts, such as commonality, outsourcing, standardization, product platform, functionality, and interdependence between modules. These conceptual elements emerge as significant characteristics to be taken into account when applying modularity in both design and production decisions and strategies. This chapter improves the alignment between the conceptual elements and their respective influences in terms of MID-MIP trajectories.

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analysis in the perspective of automotive assemblers and suppliers. Product: Management & Development, v. 11, n. 1, p. 24-32, 2013.

[4] KUBOTA, F.I.; CAUCHICK MIGUEL, P.A.; HSUAN, J. Analysis of the theoretical relationships between product and production modularity and their implications in the automotive industry. Proceedings of the 22nd EurOMA Conference, Neuchâtel, Switzerland. 2015.

[5] KUBOTA, F.I.; HSUAN, J.; CAUCHICK MIGUEL, P.A. Theoretical analysis of the relationships between modularity in design and production. International Journal of Advanced Manufacturing Technology, 2016. DOI: http://dx.doi.org/10.1007/s00170-016-9238-4.

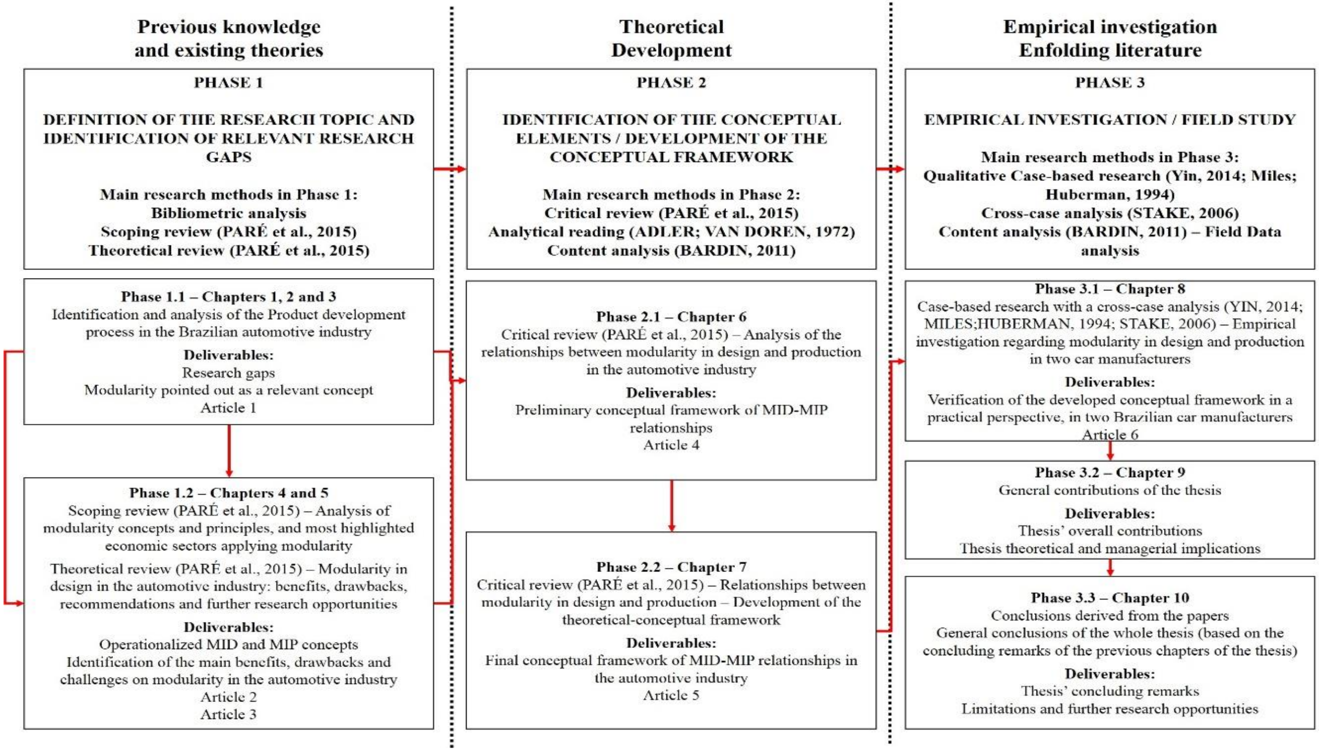
Chapter 8 describes the field study conducted in this thesis (contents of the sixth article[6]) and demonstrates the empirical analysis of the final conceptual framework through a cross-case study of the MID-MIP relationships of two car manufacturers operating in Brazil. The chapter suggests that both companies apply MID and MIP relationships, though they differ in terms of their emphasis on the application of modularity. While one company applies modularity focused on design activities, with limited changes to the MIP perspective, the other applies modularity with a greater balance between the MID and MIP perspectives. Chapter 8 demonstrates the existence of MID and MIP relationships in the context of the managerial perspective. Additionally, this chapter points to various contingencies in MID-MIP relationships, such as the choice between local and global suppliers and the relationships between strategic planning and the application of modularity.

Chapter 9 discusses the theoretical and practical contributions brought by the development of this thesis, by highlighting the contributions of the primary literature analysis, the conceptual framework of MID and MIP relationships, and the empirical study. Furthermore, the chapter points out the managerial implications that the research could bring to practice.

Lastly, Chapter 10 concludes the thesis by summarizing the main points with regard to MID–MIP relationships and their implications (both theoretical and practical), taking into account the field research. Additionally, it presents the research limitations and constraints faced during the data collection process, as well as further research opportunities. Figure 1.1 illustrates the structure of the thesis.

[6] Working paper to be submitted to Production Planning & Control (B1 – Qualis-Capes).

Figure 1.1 – Thesis structure



Source: structure adapted from Lopes (2015)

As can be seen in Figure 1.1, the first stage of the thesis focused on identifying the product characteristics of the automotive industry as a whole, investigating specifically the main characteristics of vehicle development in one part of the Brazilian automotive sector. At this stage, modularity emerged as a relevant topic, together with other important research gaps. These findings and results were related to the first specific objective of this thesis. Then, the research focused on operationalizing[7] the concepts of MID and MIP, whose characteristics and relationships are explored later in the thesis in order to build the conceptual framework. Next, the theoretical development of the thesis was carried out (Phase 2). This involved a literature review focused on the relationships between MID and MIP and the construction of a conceptual framework for these relationships. Phase 2 fulfilled the second specific objective of the thesis. Finally, Phase 3 comprised the empirical investigation, or the field study to verify the conceptual framework in an industrial context. This investigation fulfilled the third specific objective, which was to verify the conceptual framework in an empirical perspective.

[7] In this thesis, “operationalize” means the building of MID and MIP concepts that have clear conceptual elements that permit the thesis to identify the main characteristics of modularity in order to make the theoretical and empirical investigation more traceable and measurable.

2 RESEARCH METHODS

To accomplish the objective of this thesis, as stated in Chapter 1, it was critical to choose and develop robust research methods (BOER et al., 2015). This chapter describes the research methods and procedures employed to conduct this work. It also presents the basis for each decision and strategy. The chapter is organized around three major topics: (i) the literature review, part one; (ii) the literature review, part two; and (iii) the empirical work. Figure 2.1 illustrates these topics and the steps necessary to address them. The theoretical phase was subdivided into two stages (parts one and two). The first part comprised a scoping review, which was designed to provide an initial indication of the potential size and nature of the available literature on the topic of interest (PARÉ et al., 2015). This step was important for examining the extent, range, and nature of the literature on modularity, as well as for building a comprehensive approach to the main opportunities in the modularity field of knowledge. In this sense, part one of the literature review targeted the research gaps that inform the development of the thesis objectives and serves as a primary definition of the research methods.

The second part of the literature review also began by following the scoping review logic; however, it also developed several inclusion and exclusion criteria (as recommended by PARÉ et al., 2015) for selecting the articles for analysis. These criteria narrowed down the research to the automotive industry as the main context of modularity application and helped to select and filter articles exploring MID and MIP concepts and characteristics. Then, the articles analyzing MID–MIP relationships were synthesized and examined following the critical review method. A critical review is useful for analyzing the extant literature on a broad topic to uncover weaknesses, controversies, or inconsistencies in order to highlight problems and discrepancies to give direction to further improvements (COOPER; HEDGES, 2009; PARÉ et al., 2015). In this thesis, the critical review was important for revealing contradictions in the relationships between MID and MIP, as well as in the trajectories of these relationships. Thus, part two of the literature review was important for accomplishing the first[8] and the second[9] specific objectives of this thesis.

Lastly, the empirical phase consisted of the procedures for collecting and analyzing data on two automakers that applied modularity in both design and production. To accomplish the objectives of this thesis, the case study method was selected. Case studies are useful for providing explanations of linkages among phenomena, and they are preferred when analyzing real events (VOSS et al., 2002), such as the modularity applications of car manufacturers. This phase related to the third specific objective[10]. In the following, each of these three phases is described.

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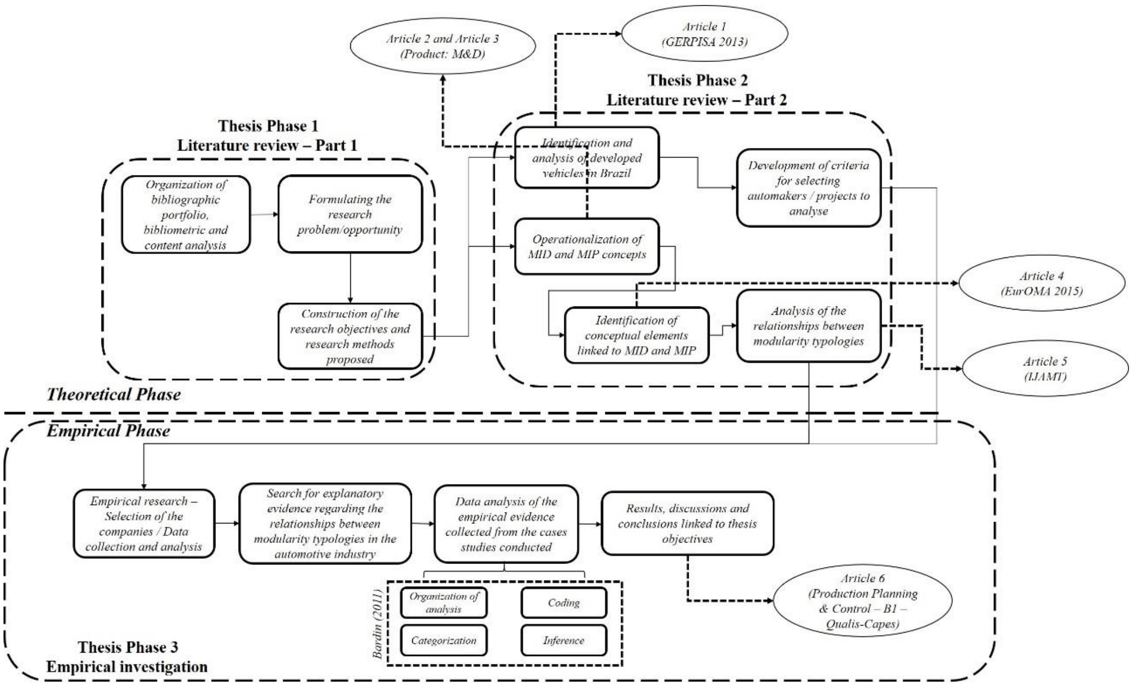
[8] SO1: Identify and analyze the similar and dissimilar characteristics of the most relevant automotive vehicle projects and automakers with respect to their applications of modularity and their contributions to the automotive industry in terms of innovations.
[9] SO2: Identify the main conceptual elements of modularity and analyze how they establish relationships between MID and MIP.
[10] SO3: Verify the relationships between MID and MIP and how they can generate benefits and/or limitations in terms of organizational and technical decisions in car manufacturers.

Figure 2.1 – Thesis research methods. Straight lines: flow of the research methods steps. Dotted lines: flow of the papers originated from the thesis



2.1 LITERATURE REVIEW – PART 1: DEFINITION OF THE RESEARCH SCOPE AND GAPS

The first phase was a broad literature review (part one), which was a wide-ranging step that was valuable for building a comprehensive approach (PARÉ et al., 2015). A search of the Scopus, ISI Web of Knowledge, Engineering Village (Compendex), Wiley Online Library, Blackwell, and SciELO databases was conducted, and other papers published by other entities were considered (Inderscience[11]). Diversifying the databases was important for enhancing the search for papers on the topic of modularity and for minimizing the potential of overlooking relevant papers in the final portfolio. In order to conduct this preliminary search, a broad keyword search was conducted for the term "modularity," since this is the most used keyword in modularity-related papers (CAMPAGNOLO; CAMUFFO, 2010). This first search yielded 1,787 articles with a broad approach regarding modularity and its typologies, industrial focus, and objectives. Following the removal of duplicate papers, the portfolio comprised 1,475 articles.

Next, an inspectional reading of the titles, abstracts, and keywords of these papers was conducted, with the goal of quickly identifying both the papers that explored modularity from the industrial and/or managerial perspective and the sectors most frequently applying the concept (ADLER; VAN DOREN, 1972). This procedure produced 576 papers. Then, only those papers exploring both MID and MIP were considered, yielded 307 papers. Furthermore, only the most recent articles (at the time of developing the theoretical background of this thesis; papers from 2008 to 2012) were taken into account in order to identify the most recent and fruitful opportunities for further research. In addition, this portion of the study represented a literature update of a research study conducted by Carnevalli and Cauchick Miguel (2009), which examined the period between 1998 and 2008. To ensure that all relevant papers were included, important studies in terms of modularity applications and promising research gaps were also analyzed.

From this analysis, 154 papers were ultimately retrieved. The analysis also explored emerging topics, research gaps, and further research opportunities through an analytical reading, as recommended

[11] Examples of journals of interest in this database include: the International Journal of Automotive Technology and Management, the International Journal of Technology Management, and the Journal of Manufacturing Technology Management.

elsewhere (ADLER; VAN DOREN, 1972). EndNote X6® was used to record and store the papers. This portion of the analysis revealed that the automotive industry is one of the most frequently considered sectors when applying modularity, as corroborated by Shamsuzzoha (2011), who indicated that the sector offers promising opportunities for research.

2.2 LITERATURE REVIEW – PART 2: CONCEPTUAL FRAMEWORK BUILDING AND DEFINITION OF THE INDUSTRIAL CONTEXT

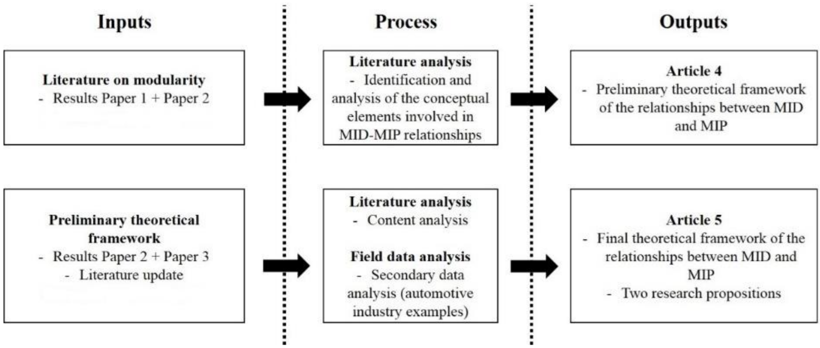
This section presents the main stages of defining the investigated industrial context (i.e. the automotive industry), as well as the steps following to build the conceptual framework of MID–MIP relationships. The primary keywords searched during the second part of the literature review (in addition to "modularity") were "modularisation," "modularization," "modular design," and "modular product," combined with "automotive industry" and "auto industry." During this stage, the focus was on the bibliometric analysis of several characteristics of the examined papers, including the research methods, the most-cited industrial sectors applying modularity, and the most-cited benefits and drawbacks of modularity. The theoretical papers were classified into four subgroups: theoretical–conceptual, literature review, simulation, and theoretical modeling. The empirical papers were categorized into surveys, case studies (single or multiple), action research studies, and experiments.

Data derived from the bibliometric analysis was useful in identifying the main types of modularity exposed in the literature and the most highlighted industrial contexts for modularity applications. MID emerged as the most investigated modularity typology (followed by MIP), and the automotive industry emerged as the primary industrial context considered when studying modularity, confirming what was identified in the first part of the literature analysis (see previous section). These results guided the content analysis, which focused on MID and MIP, the two most common modularity approaches in the literature (JACOBS et al., 2011). In this step, this thesis examined the taxonomy of modularity concepts found in the articles (as suggested by PARÉ et al., 2015), in order to build definitions for MID and MIP through an analysis of the definitions of modularity found in each study. These research steps and their respective results comprise the contents of the first and the second articles of this thesis, presented in Chapters 3 and 4, respectively.

Next, a literature update was conducted to retrieve articles published between 2013 and 2015 to enhance the theoretical findings with updated publications, following the procedure used by Campagnolo and Camuffo (2010) in a literature review about modularity in management studies. From this update, the final portfolio of papers comprising conceptual framework of MID–MIP relationships in the automotive context was determined. This final portfolio comprised 61 references drawn from the engineering and management literature and restricted to the automotive industry context. These articles focused mostly on the impacts of MID and MIP on such aspects as company performance, performance integration, supply chain integration, and complex product management. A limited number of articles focused specifically on the relationships between MID and MIP, suggesting an unexplored field of research and a need for more research in this direction (CAMPAGNOLO; CAMUFFO, 2010; JACOBS et al., 2011; LUCARELLI et al., 2015).

Next, the 61 retrieved articles were examined to identify the main conceptual elements related to modularity. The analysis was conducted through a preliminary inspectional reading (according to ADLER; VAN DOREN, 1972) focused on (i) finding the main concepts and definitions of modularity in the analyzed articles and (ii) identifying the main concepts and elements comprising these definitions. Following the inspectional reading, a critical review based on Paré et al. (2015) was carried out to verify the MID-MIP relationships and their inconsistencies. Finally, the conceptual elements of modularity (e.g. commonality, functionality, outsourcing, etc.) were extracted from the literature in order to establish the connections between MID and MIP and the trajectories of these relationships. Finally, the research culminated in the development of a conceptual framework representing the theoretical relationships between MID and MIP. The main results of this part of the thesis are presented in Chapters 6 (contents of the fourth article) and 7 (contents of the fifth article). Figure 2.2 summarizes the development of these steps.

Figure 2.2 – Steps to develop the conceptual framework of MID-MIP relationships



2.2.1 Choice of automotive industry as the context and companies' selection for the field study

As mentioned previously, the automotive industry emerged as the most highlighted sector applying modularity. In addition, the automotive industry was selected as the context of analysis due to its intense competition, through which product platform design and modularity serve as means for creating customization, variety, and shared components (HOLWEG, 2008). The thesis focused specifically on the development of passenger cars, since these are among the most complex vehicular products traded worldwide (OEC, 2015). Automobile firms must change and constantly learn more about their products and processes in order to attend to market demands, and modularity might be important in this learning process (WAGNER et al., 2015), especially given the inherent complexity of vehicle design and assembly. Considering that modularity can reduce product complexity (BALDWIN; CLARK, 2000; LUGO-MÁRQUEZ et al., 2016; MA; KREMER, 2016), this thesis considered the specific application of modularity to the context of car production to be a relevant research opportunity.

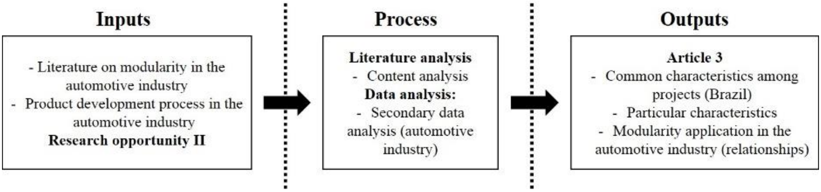
Little research has yet explored the implications of product architecture for organizational design in the automotive industry; thus, it is relevant to investigate the possible integration mechanisms that enhance the connections between modular product architecture and modular production, as identified by the literature (e.g. RO et al., 2007; LIAO et al., 2013). More investigations of modularity in this industry are needed (CABIGIOSU et al., 2013). In addition, despite the effective strategic use of modularity by a few automotive firms, in the automotive industry, there is still a limited understanding of what modular strategies really mean and the organizational changes necessary to implement them effectively (SANCHEZ, 2013).

Once the automotive industry was selected as the thesis' industrial context, the next step was to define the criteria for selecting companies for the empirical work of the thesis. This step improved the rigor and robustness of the empirical phase (SOUSA; VOSS, 2001). Then, the thesis carried out a scoping review to identify and analyze the main characteristics of automotive projects developed in the Brazilian market. The Brazilian automotive industry was selected as the specific context because this industry is responsible for the largest range of automobile brands being produced in a single country (PARENTE et al., 2011). Numerous new entrants have arrived in the Brazilian market in recent years; thus, Brazil is a relevant environment for both theoretical and empirical investigations (ZILBOVICIUS et al., 2002; PARENTE et al., 2011).

The focus of this step was the product development process in the automotive industry, in which it was possible to identify relevant characteristics, such as local R&D centers, tropicalization processes, and suppliers' involvement in product design activities. To complete the analysis, some primary data from previous studies, such as paper notes[12] recorded from lectures involving automotive managers and practitioners, were examined. Additionally, theses and master's theses covering the subject of "vehicle development in Brazil" were also considered. By the end of this step, five projects from five different automakers had been considered for further investigation. It is important to note that this part of the research only analyzed the first versions/models of these five vehicles launched to the market. The main emerging feature in all analyzed projects was the application of modularity, although each project had a distinct focus. The findings of this step confirmed the relevance of modularity in the automotive industry context, as pointed out by other publications (e.g. CABIGIOSU et al., 2013; SANCHEZ, 2013; LUCARELLI et al., 2015). This analysis yielded the results of the third article of this thesis. Figure 2.3 summarizes this process.

[12] For instance: notes from a General Manager's lecture of one of the investigated automakers and the description of the vehicle's engineering, functionalities and design and process management.

Figure 2.3 – Steps to identify and analyze the characteristics of the vehicle development in Brazil



To select companies for the empirical study, the relevant criteria were those developed during the identification and analysis of common and particular features of developed vehicles in Brazil. These criteria required companies to:

(i) Conduct their initial product development process phases primarily through Brazilian engineering;
(ii) Have maturity and experience in modularity adoption in a way that made it possible for them to understand the effects and results of the application of modularity;
(iii) Be among the 50 most innovative companies between 2013 and 2015, according to the Boston Consulting Group (BCG) (WAGNER et al., 2013; 2014; RINGEL et al., 2015) and;
(iv) Provide access for visits and data collection.

Once these criteria were established, an analysis was conducted to determine which companies fit the requirements. The result was a list of six automakers that complied with all established criteria. Next, all six car companies were contacted to solicit their participation in the research. Of these, four declined because they considered the research subject to be too strategic to provide data, and the other two companies agreed to participate in the field study.

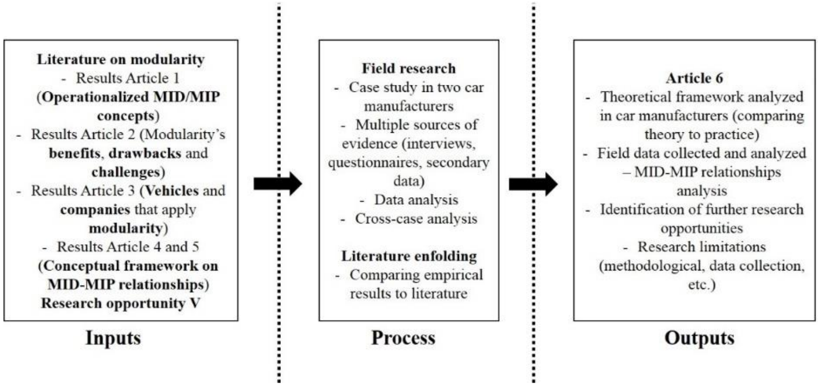
2.3 EMPIRICAL PHASE: CASE-BASED APPROACH PLANNING AND CONDUCTION

The empirical phase (field study) was important for verifying the relevance and applicability of the conceptual framework developed in order to determine whether the conceptual elements identified in the theoretical phases represented, in practice, the application of modularity in the studied automotive companies. To achieve this empirical verification, a case-based approach was selected. An approach through case study is valuable for investigating contemporary phenomena in depth and within real contexts, especially when the boundaries between a phenomenon and its context are not evident (YIN, 2014). In addition, case-based research is appropriate for this study because of the explanatory nature of the research question (VOSS, 2009; YIN, 2014). The exploratory aspect of the research question creates an opportunity to observe and identify interesting, relevant, and potentially counter-intuitive phenomena that are not thoroughly explained by existing theory (PERSSON; AHLSTRÖM, 2006; BOER et al., 2015). Thus, case studies can offer beneficial theoretical results by deepening comprehension of studied phenomena and identifying possible contingencies (TSANG, 2014). It is noteworthy, however, that the purpose of generalizing results is not to generalize them to other empirical contexts or units of observation, since each empirical context is unique (KETOKIVI; CHOI, 2014).

Therefore, case-based research was considered suitable for the empirical part of this thesis. Through the case studies, it was possible to generate new insights regarding the concepts of modularity and the relationships between MID and MIP in terms of: (i) technical and organizational aspects, such as design compatibility and the alignment between product platform and production architecture, and (ii) theoretical aspects, such as the conceptual elements that build MID–MIP relations. The main object of analysis was the modularity practices and decisions of two Brazilian car manufacturers, since it was through these modularity activities that the conceptual framework could be verified.

To enhance the results of the case study, this thesis followed Stake’s (2006) model to conduct a cross-case analysis as a methodological approach to deepen comprehension and explain the investigated phenomenon (MILES; HUBERMAN, 2014) and enhance the comparison of the analyzed phenomenon in both companies (YIN, 2014) by identifying similar and, mainly, dissimilar aspects of the studied cases (STAKE, 2006). This analysis was also designed to support different decisions and approaches related to the investigated topic and to prevent researcher bias (VOSS, 2009). Figure 2.4 summarizes the results of the theoretical phases, as well as the development of the field research phase and the results of the data collection and analysis. Next, sections 2.3.1 and 2.3.2 present the methodological procedures for collecting and analyzing the data gathered during the field study.

Figure 2.4 – Steps and methods to develop the field study and its results



2.3.1 Data collection procedures

Multiple sources of evidence were explored to increase construct validity. The first task was to send out a questionnaire (see Appendix D) to obtain general information regarding the investigated companies' modularity adoption approaches. From the responses, it was possible to understand the automakers' goals in applying modularity and the main implications, benefits, drawbacks, and changes that originated from the strategy. The next task was to develop an interview protocol (Appendix E) that was revised by an expert in the field of modularity. The revision of the protocol by an expert was important to increase the understanding of the questions as well as their relevance in terms of the alignment with the thesis objectives. In addition, the expert was selected because of his background in production engineering and management, his work on modularity for approximately 10 years (both theoretically and empirically), and extensive experience by researching the automotive industry, including publications on modularity in this industrial sector.

Next, the interviewees in each company were carefully selected, since the proper selection of interviewees augments data quality (BARDIN, 1977). Thus, the following people were selected:

- From the first automaker: a manager from the systems and engineering department, a general manager, and an engineer from the projects department;
- From the second automaker: a manager from the R&D department, a manager from the product development

department, and a former manager from the simulation and finite elements department.

Those experts were selected because they were tightly involved in the product development process in their respective companies, thus having deep knowledge regarding both the product design and production phases. This enabled having suitable amount of information to be analyzed afterwards. Each interview lasted approximately one and a half hour and was recorded via paper notes (in both companies) and audio recordings (in only one of the companies). These data were transcribed immediately after the interviews in order to avoid losing important information and insights that emerged during the conversations, as has been recommended elsewhere (VOSS, 2009; CAUCHICK MIGUEL, 2011). Finally, the data analysis was conducted, as presented in the next section.

2.3.2 Data analysis procedures

The data analysis decisions and activities were conducted as iterative processes. Questionnaires and interviews were analyzed more than once in order to revisit obtained information, analyze whether the information gathered was coherent, and obtain new insights, as recommended by Zirpoli and Becker (2011b). This thesis also combined the recommendations of Bardin (1977), Miles and Huberman (2014), and Yin (2014) to carry out the data analysis and inferences as follows:

- Data organization: Data collected from the interviews were electronically written and organized directly after conducting the interviews. Data collected from the questionnaires with the managers were organized together with the field notes from the interviews. Data from both sources of evidence were aligned to support further analysis and then organized into four groups (i.e. modularity application objectives, the impact of MID in production, MIP and manufacturing limitations of MID, and common practices of MID and MIP), following the previously mentioned variable definitions. This yielded a systematic data organization scheme that facilitated the researchers' further coding and data reduction.
- Coding and data reduction: After the data were organized into the aforementioned groups of variables, coding was

used in each group to allow a systematic and precise description of the outcomes originating from the field study. Data regarding conceptual elements involved in the application of modularity and the MID–MIP relationship trajectories were reduced and coded. Coding was also used organize data and establish patterns for further data triangulation.

- Categorization and identification of interrelations: This step helped to identify the relations among the conceptual elements identified during the study. Additionally, a map was built to illustrate the patterns and relationships among concepts, as suggested by Miles and Huberman (1994). Semantics criteria were used to establish the interrelations among conceptual elements from the literature and the empirical evidence. This step helped to reduce the data and simplify the overall analysis (BARDIN, 1977). Before beginning the inference step, data collected after the initial data collection (e.g. questions sent by e-mail) were gathered and analyzed together with the data from the questionnaire and the interviews in order to gain additional insights.
- Data inference: This was an iterative process. Interviews, questionnaires, and field notes were revisited to build the results and analysis. MID–MIP relationships were analyzed from the conceptual elements perspective using the hypothetical–deductive method, as proposed by Nunes and Bennett (2008). Through the interviews and questionnaires, the study identified several conceptual elements from the field (e.g. commonality, co-designing with suppliers, and product platforms). Then, the ways in which these elements connected MID and MIP in the investigated companies were established, and the results were compared with the conceptual model built through the literature. This enabled the analysis of the MID–MIP relationships and the building of the framework adopted by each automaker.

This process yielded both the conceptual frameworks applied by the two car manufacturers and several conclusions drawn from the analysis of the framework and the empirical evidence. These results can be found in the last article of this thesis (presented in Chapter 8). Figure 2.5 shows the detailed steps followed to develop the thesis chapters (articles). Additionally, Table 2.1 shows the relationships between the articles and the specific objectives. The overall objective was divided into three specific objectives ("SO1," "SO2," and "SO3"), each of which followed its own research methods and procedures and generated parts of the thesis' overall results/contributions. These results are represented by the papers, which were submitted to international conferences and journals. The following chapters (Chapters 3, 4, 5, 6, 7 and 8) present the articles that compose this thesis.

Figure 2.5 – Inputs, processes, and outputs of each thesis step (with the articles as partial deliverables)

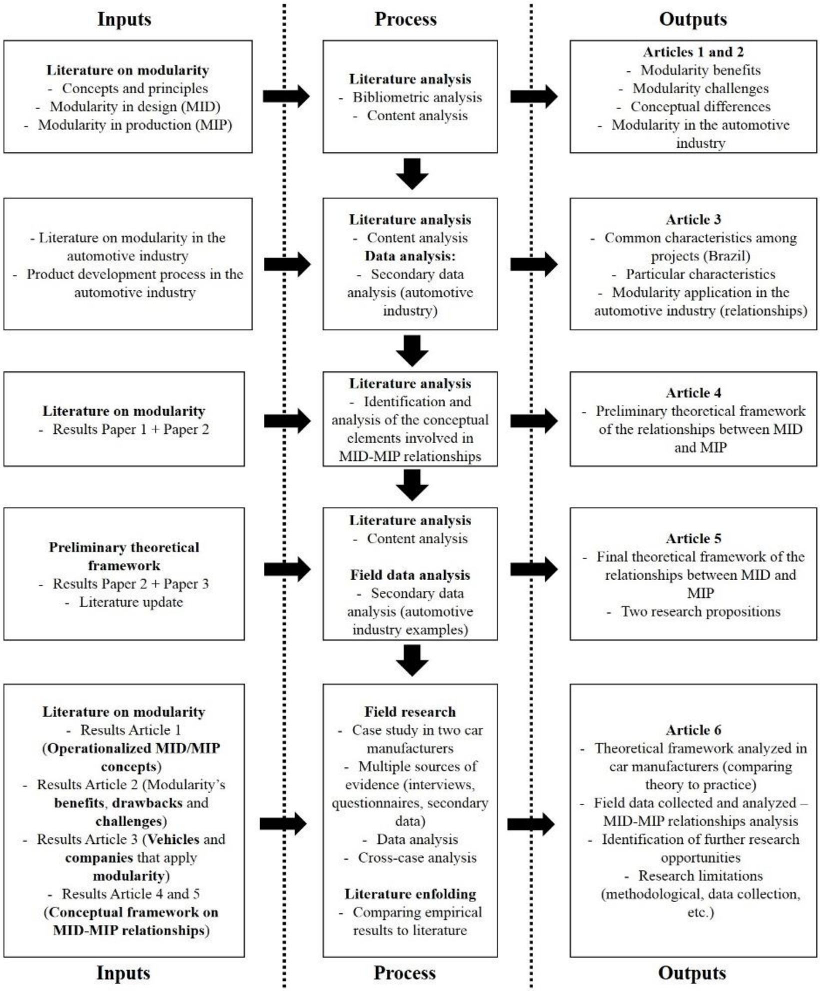


Table 2.1 – Relationships between the articles and specific objectives

Thesis main objective	**Thesis specific objectives (SOs)**	**Articles (A) titles**	**Research methods used**	**Main results / Contribution to the doctoral research**	**Submitted to/Published in**
OO: Identify and analyze the relationships between MID and MIP in the automotive industry in order to better understand the main benefits, limitations, and possibilities when establishing MID–MIP relations	SO1: Identify and analyze the common and particular characteristics of the most relevant automotive vehicle projects and automakers with respect to their applications of modularity and the innovations that their projects brought to the automotive industry	A1 – Identification and analysis of characteristics of development of vehicles in the Brazilian automotive industry	• Systematic literature review • Scoping review (PARÉ et al., 2015)	• Systematized analysis of the main vehicles developed in the Brazilian market • Identification of modularity as a relevant strategy in the Brazilian automotive industry • Building criteria for selecting the companies to be investigated in future field study	GERPISA 2013 Conference (Published)
	SO2: Identify the main conceptual elements of modularity and analyze how these elements establish	A2 – Towards a contribution to modularity concepts and principal domains	• Scoping review (PARÉ et al., 2015) • Content analysis	• Operationalization of MID and MIP concepts	Product: Management & Development (Published)
		A3 – Design modularity:	• Bibliometric analysis	• Identification of modularity's main	Product: Management &

	relationships between MID and MIP	identification of its benefits and difficulties through a bibliographical analysis in the perspective of automotive assembler and suppliers	• Theoretical review (PARÉ et al., 2015) • Content analysis	theoretical benefits and drawbacks in the automotive industry • Identification and analysis of the main research opportunities in the modularity field	Development (Published)
		A4 – Analysis of the theoretical relationships between product and production modularity and their implications in the automotive industry	• Critical review (PARÉ et al., 2015) • Content analysis	• Identification of the main conceptual elements involved in MID–MIP relationships in automotive companies: co-design with suppliers, commonalities, functionalities, inter-module interdependence, product platforms, outsourcing, and standardization	EurOMA 2015 Conference (Published)

		A5 – Theoretical analysis of the relationships between modularity in design and production	• Critical review (PARÉ et al., 2015) • Content analysis	• Analysis of the relationships and trajectories of MID–MIP relationships • Analysis of how each conceptual element (identified in P4) are involved in MID–MIP relationship trajectories	International Journal of Advanced Manufacturing Technology (Published)
	SO3: Verify the relationships between MID and MIP and determine how these relationships can generate benefits and/or limitations among car manufacturers	A6 – Relationships between modularity in design and production: a field study in two car manufacturers	• Case-based research • Cross-case analysis (MILES; HUBERMAN, 2014; YIN, 2014; STAKE, 2006)	• Empirical analysis of the theoretical framework of MID–MIP relationships • Analysis of the main decision drivers when establishing MID–MIP relationships • Identification of emerging contingencies of MID–MIP relationships	Production Planning & Control (Working paper)

3 IDENTIFICATION OF COMMON AND PARTICULAR DEVELOPMENT CHARACTERISTICS AND THE ROLE OF MODULARITY IN VEHICLE DESIGN AND PRODUCTION IN BRAZIL

This chapter presents the findings originated from the analysis focused on the automotive industry scenario. That is, this chapter exposes the contents of the first article[13] developed in this thesis. It identifies and analyses the common and specific features in locally developed passenger cars that have brought competitive advantages in new product development in the Brazilian automotive industry. It also presents the main characteristics of vehicle development in the Brazilian automotive industry, with modularity being highlighted among them.

3.1 THE BRAZILIAN AUTOMOTIVE INDUSTRY CONTEXT

A new competition scenario in Brazil emerged from the market opening in the 1990s. Inflation reduction and a new free trade agreement among Brazil, Argentina, Uruguay and Paraguay became the national consumer market more demanding and more competitive (SANCHEZ et al., 2012). This has occurred also due to the growing competition and the customers' search for products more suitable to their needs and expectations in many industrial sectors, among them the automotive.

Although the automotive industry is widely regarded as one of the most global sectors, it remains geographically dominated by determined regions. An overall vision of the automotive sector shows that the annual automobile production represents only 1% of the worldwide population and it is concentrated in large markets such as North America, Western Europe and Asia and Pacific. These markets account for more than 90% of international production volume and about 70% of passenger car production in recent years (HUNG, 2007; IBUSUKI et al., 2012).

However, these traditional (or mature) markets suffer due to a natural saturation and, as a consequence; their automotive industries consider the BRIC nations (Brazil, Russia, India, and China – emerging economies) as a solution for survival and expansion (HUNG, 2007). Subsequently, the emerging markets are accounting for more share,

[13] KUBOTA, F.I.; CAUCHICK MIGUEL, P.A. Identification and analysis of characteristics of development of vehicles in the Brazilian automotive industry. **Proceedings of the 21st Gerpisa International Colloquium**, Paris, France. 2013.

declining the 'Triad' region (North America, Western Europe, and Japan) and only a portion of automotive production (IBUSUKI et al., 2012). Brazil was one of the countries that has received most automotive manufacturers plants in the world (CARDOSO; KISTMANN, 2008), with estimates of 13 automakers and investments around US$ 6.5 billion until 2014 (SASAKI, 2012). Since the OEM pioneers other newcomers have arrived in the country (see Table 3.1). This shows that since its introduction in Brazil, the automotive sector has undergone important changes concerning location and positioning of product development activities and the organization of production processes within the context of companies working in this supply chain (SALERNO et al., 2009).

Table 3.1 – Entry of the carmakers in Brazil

Group	**Entry Year**	**Automakers**
Pioneers	1919 1925	Ford General Motors Note: assembly of components imported from the headquarters
First Followers	1956-58	Volkswagen Chevrolet Ford Toyota (off-road land cruiser)
Second Followers	1971	Fiat
Third Followers	1990's	Honda, Audi, Daimler, Mitsubishi, PSA-Peugeot, Citroën, Renault, Toyota (passenger cars), Nissan, Hyundai
Late Followers	2000's onward	Hyundai (2012: assembling of HB20 car), BMW (2013: in process of installation)

Source: adapted and updated from Amatucci (2010).

In this sense, Brazil along with other emerging markets has contributed to lead of this changing process, which is an aspect already pointed out by Marx et al. (1997) more than a decade ago. Therefore, considering this scenario and the automotive industry growth in Brazil from the past two decades, this paper identifies and analyses the common and specific features in automobiles that brought competitive advantages in new product development (NPD) within the Brazilian automotive industry. The study aims to contribute to a theoretical framework regarding the main characteristics that influence the success of vehicle development in the country.

After this introduction, the paper is structured as follows: section 3.2 presents some aspects regarding automotive industry NPD in Brazil. Section 3.3 show the material and methods adopted to develop the study. Section 3.4 presents the results and discussion about the main findings. Finally, section 3.5 offers some concluding remarks and further research opportunities emerged from this work.

3.2 RELEVANT FACTORS FOR NEW PRODUCT DEVELOPMENT IN THE BRAZILIAN AUTOMOTIVE INDUSTRY

It is possible to confirm the Brazilian automotive sector evolution and growth when observing the market share expansion of this segment since the market opening in the 1990s. Data from the National Association of Automobile Manufacturers (ANFAVEA) indicate an increase of 10.5% (9.1% in 1990 to 19.5% in 2010) share in the country's industrial Gross Domestic Product (GDP) (ANFAVEA, 2011). In addition, Brazil is in fourth place in the manufacturing ranking of car and light commercial vehicles, with 3,425,437 units sold in 2011, equivalent to about 3% more than the 2010 volume and approximately 2 million units more than in 2003, showing an increase of almost 150% since that period, according to National Federation of Motor Vehicles data (FENABRAVE, 2011).

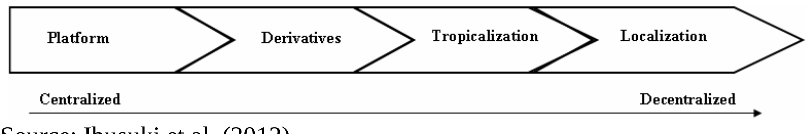
In this context, it is remarkable that in the search for competitive advantages and higher quality products, companies are the main innovation agents. However, organizations do not innovate and learn isolated but with interaction or exchange between competitors, suppliers, and customers, with public research institutions, universities, and other knowledge generation bodies such as standardization and research institutes (IBUSUKI et al., 2012). These aspects are corroborated by Scholtissek (2012), which states that rare innovations reach market success without any kind of cooperation (partnerships, alliances, networks, etc.) because it provides access to goods and useful and complementary skills.

Thus, it is clear that OEMs are showing a better understanding of this scenario, by investing more in local and emerging markets. Automakers such as General Motors (GM), Renault, Ford, Volkswagen (VW) and Fiat, for example, are organizations that have product R&D centers in Brazil (CAUCHICK MIGUEL, 2006; SEGISMUNDO; CAUCHICK MIGUEL, 2010; IBUSUKI et al., 2012; AMATUCCI;

MARIOTTO, 2012). These R&D centers aim to design and develop local products for emerging markets, considering regional characteristics and needs and expectations from local customers. From these centres, vehicles such as Meriva (GM), Sandero (Renault), EcoSport (Ford), Fox (VW) and the New Uno (Fiat) have been developed focusing the Brazilian market (CAUCHICK MIGUEL, 2006; SEGISMUNDO; CAUCHICK MIGUEL, 2010; IBUSUKI et al., 2012).

In addition, other changes in Brazilian automotive industry that emerged in recent years refer to the introduction of industrial condominiums, adoption of the modular strategy, dissemination of best operating practices throughout the chain, the supply process selection, and the role of local product design management (SALERNO et al., 2009). Simultaneously, the product platform concept has become a key concept in the innovation process, since this can have a strong impact both in the way the product is developed as in the innovation process as a whole. This concept includes the relationship with suppliers and customers and offers greater product range (MIKKOLA, 2006), savings in material selection (JOHNSON; KIRCHAIN, 2009) and economies of scale and scope (PASCHE; SKÖLD, 2012). Ibusuki et al. (2012) argue that platforms tend to keep developed centrally (i.e. inside the automaker headquarters) while the development of derivatives (or derivative products from platforms) can be decentralized through foreign automakers units. Regarding this topic, Figure 3.1 illustrates the different levels of centralization and decentralization in product development competencies. In the next section, the research methods are showed.

Figure 3.1 – Product development in terms of development competencies.



Source: Ibusuki et al. (2012)

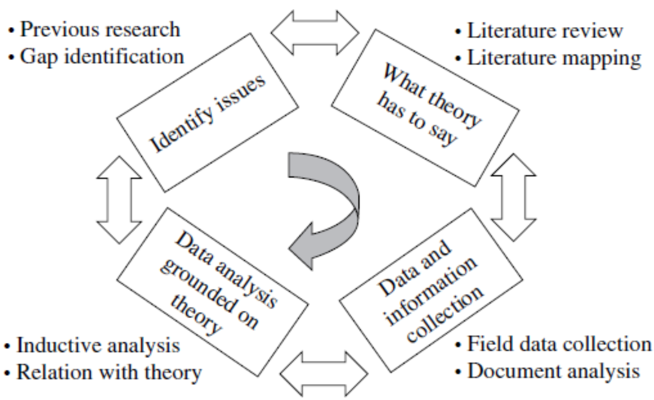
3.3 RESEARCH METHODS

Considering the objective of this study, this paper is classified as a theoretical-conceptual research (refer to NAKANO, 2010), since literature investigation on the topic “vehicle development in Brazil” was conducted through the literature of Brazilian vehicle development with further systematization and analysis of the data and information. The following sources regarding “automotive vehicle development in Brazil were considered in for analysis: articles, Ph.D. thesis, master dissertations, books, professional magazines, technical lectures (by automaker representatives), and in loco visits. In addition, specific websites were taken into account for complementary evidence, considering the quality and reliability of this kind of sources.

For data analysis, hypothetical-deductive methods (NUNES; BENNETT, 2008) were applied to systematize common and particular features in vehicle development in the country and their influence regarding the competitive advantage generation. Thus, it aims to enhance comprehension about the relevant factors in the subject as well as to identify issues that contributed to the place of each studied automobile in their specific market.

The vehicles analyzed in this research were: Meriva (GM), EcoSport (Ford), Fox (VW), Sandero (Renault), and New Uno (Fiat), launched respectively in 2002, 2003 (both EcoSport and Fox), 2007 and 2010. It is important to point out that the first versions of each car were considered, i.e. during the following years, most of them have had incremental and/or radical changes in their design. Additionally, these five vehicles were chosen because they were specifically developed for the Brazilian and other emerging markets. Figure 3.2 summarizes the analytical process framework used as the research methodological approach.

Figure 3.2 – Research cycle process and analytical process steps.



Source: Cauchick Miguel (2006)

3.4 IDENTIFICATION AND ANALYSIS OF COMMON AND SPECIFIC CHARACTERISTICS OF DEVELOPMENT OF VEHICLES IN THE BRAZILIAN AUTOMOTIVE INDUSTRY

This section describes the common and specific features from the Brazilian vehicle development. Aspects such as product design, motorization options, competitive differentials, among others were investigated. In addition, once these features were identified, they were systematically organized towards a broad theoretical framework concerning factors influencing the vehicle development process in the Brazilian market.

3.4.1 Common characteristics

3.4.1.1 R&D centers and locally commanded design

All vehicles analyzed were developed in Brazil, i.e. domestic subsidiaries were responsible or had a significant role in the development process in terms of quantity of engineering hours and design decisions. Regarding local car development, one of the aspects considered relevant was the research and development (R&D) centers set up in the country. Salerno et al. (2003) justify this by reporting that hosting locally a product development involves managing the project in all important aspects, increasing autonomy in the suppliers' selection and participation of local firms in the supply chain. In this sense, it was noticed that all investigated carmakers (Fiat, Ford, GM, Renault ad VW) have research centers in the country, as already highlighted in literature (CAUCHICK MIGUEL, 2006; IBUSUKI et al., 2012).

The literature on this subject has increasingly emphasized the importance of R&D investments. This can be seen when analyzing the investments volume held by OEMs: a high percentage of research budgets are destined to immediate application technological activities, especially those directed to product development and new models adaptation (AMATUCCI; BERNARDES, 2009b). A recent example is Fiat, which announced that the Brazilian subsidiary would assume the responsibility of a '100% Brazilian' vehicle: the New Uno model, developed by a workforce of 850 engineers with a US$ 150 million investment (IBUSUKI et al., 2012). In addition, the examples of GM Meriva, Renault Sandero, Ford EcoSport and VW Fox were also developed in Brazil (CAUCHICK MIGUEL, 2006; SEGISMUNDO; CAUCHICK MIGUEL, 2010) and targeted specifically to fulfill national and other emerging economies markets. These vehicles have been mentioned in literature as vehicles developed in Brazil through the respective R&D centers, with investments of US$ 230 million in GM Meriva (REDETEC, 2003a), US$ 360 million in Sandero (RENAULT, 2010) and US$ 150 million in New Fiat Uno (IBUSUKI et al., 2012). No data were found about EcoSport.

3.4.1.2 Product design and development competencies

Another common characteristic observed is related to vehicle design. Most projects (except Ford EcoSport) prioritized internal design, towards providing more comfort to passengers and more luggage space. In this sense, VW Fox's highlight is the concept of "Designed Around the Passengers". GM Meriva and Renault Sandero were other cars that followed this trend of prioritising internal design, where the former used the FlexSpace concept, which provides a high configurable seating system, and the latter has a larger internal space for five passengers and luggage (METROPOLI, 2007); however, Renault Sandero seats are not configurable as the Meriva's.

Based on data available about these vehicles, it is possible to classify them as a "complete derivative" (CAUCHICK MIGUEL, 2006). However, despite Meriva was developed within Brazil, the European market was also considered due to the need for learning and development concerning global design (AMATUCCI; BERNARDES, 2007). Thus, vehicles needed to fulfill both customers' preferences and current legislation, which differ in some aspects compared to other markets in particular developed countries.

In VW Fox's case, Amatucci and Bernardes (2009a) report that there was a focus on the Brazilian "operational scenario", i.e. considering driving conditions, fuel mixture, consumer purchasing capacity, etc. However, these aspects have also been considered by the majority of OEMs in vehicles directed to the Brazilian market, since road conditions, for example, are distinct from American and European's. In Brazil, comparing to those regions, more robust suspensions, and damping systems are needed.

Additionally, the various powertrains and fuel options (gasoline, ethanol, mixtures, etc.) correspond to a common aspect. The engine choice approach is utilized because it is considered a strategic topic for the sector's competitiveness (CERRA et al., 2011), especially in Brazil, where there is a unique fuel variety, which further drives the engine development within the country (AMATUCCI; BERNARDES, 2009b).

3.4.1.3 Modularity in design, production and use

Another common characteristic refers to the modularity strategy. In general, it is a concept that exists since the 1960s, created in the computer industry, bringing competitive advantage and demonstrating considerable importance in product development process (ARNHEITER; HARREN, 2006). The modular strategy consists in decomposing complex products in subsystems that constitute complete functional units, which can be designed and manufactured independently (which allows the construction of different products through combining subsystems), but functioning as a whole (BALDWIN; CLARK, 1997; PERSSON; AHLSTRÖM, 2006).

In GM Meriva's case, it was found characteristics of modularity in design and, some of them in use. Amatucci and Mariotto (2012) report that the vehicle has parts and components harnessed from Corsa and Astra, which also are vehicles designed by GM. Besides, customers can select and configure some desirable features, such as air conditioning, external color, accessories such as CD or DVD player, etc. (CHEVROLET, 2012). Concerning VW Fox's project, the vehicle has subsystems that connect the vehicle as a whole. According to Mello and Marx (2007), six modules compose VW Fox: cockpit, rear suspension, front suspension, seats (front and rear), fuel tank and tires. Besides, aspects of modularity in use were perceived as in VW Fox, through optional features like external colors, motorisation, internal finishing, rear parking sensor, and other functional modules. (VOLKSWAGEN, 2013).

The Ford EcoSport's manufacturing plant (which also manufactures the Fiesta model) uses the synchronized production concept, where parts suppliers operate within the assembly line (Redetec, 2003b), characterizing as an industrial condominium, an intermediate level between industrial districts and modular consortium (FRANCO, 2009). Salerno et al. (2009) report that this is one of the most advanced modular plants and is located two kilometers away from the engine and transmission manufacturers (another Ford's units) and most suppliers. In this case, the modularity feature that emerges is related to the production process through the industrial condominium, where the automaker gathers its main suppliers around its factory, defining the modules being produced; it builds dedicated plants, firming supply contracts, sharing investments to be made and risks of the company (FRANCO, 2009). Lastly, modularity in use features is available in the latest Ford EcoSport versions, being able to configure some items such as external colors, CD or DVD player, sensors, etc. (FORD, 2013).

In Renault Sandero's conception, there is a clear evidence of modularity in design and use. The Sandero was divided into 30 different functions, which were associated with suppliers (panel, floor, suspensions, etc.), which participated in function development together with a Renault carmaker team (RENAULT, 2010). Concerning modularity in use, it is possible to configure specific items, according to the selected model (which varies according to engine power): external color, hydraulic steering, and steers height regulation, air conditioning, antilock brake system (ABS), airbags, etc. (RENAULT, 2013).

Lastly, the New Uno model has parts and components from other Fiat vehicles. Circular air vents were inspired in the design of Doblo model, while the instrument panel was developed based on Fiat 500 compact. Other utilized parts are commands grouped in the left-hand side of the driver (as in the Punto model) and the ceiling console (optional) inspired on Fiat Idea minivan (QUATRO RODAS, 2010b). In addition to these modularity in design features, modularity in use approach is also applied through the customisation by customers of some characteristics such as the New Fiat Uno version (depending on engine options): colours, adhesives, hot air defroster, driver seat with height mechanical adjustments, anti-theft wheel bolts kit, thermal windshields, etc. (FIAT, 2012). It is noteworthy that among the five studied vehicles in this paper, the New Fiat Uno is the project that most explored modularity in use concepts since it has a wide variety of customizable features, which is an intensive competitive advantage strategy.

3.4.2 Specific characteristics

Key aspects of the vehicle design, both global and local levels, are the characteristics that generate competitive advantages in the market. These regard to advanced factors matured in about 90 years of this industry in the country through situations such as the presence of a large number of carmakers, boosting competitiveness and the slow and gradual development of the supply and support industry, which is also globalized and high competitive (AMATUCCI; BERNARDES, 2009b). Thus, current trends aimed at product differentiation in various manufacturing areas are considered positive in general (BARBIROLI; FOCACCI, 2003), similar to what has occurred in the automotive sector.

In markets such as Brazil, even the existence of some basic design adaptations made by transnational companies' (TNCs) headquarters, subsidiaries need to conduct local adaptations which involve many aspects already mentioned before such as component materials, road conditions and quality specifications of fuel mixtures (e.g. gasoline with ethanol), among others (IBUSUKI et al., 2012).

In this sense, besides common features presented and described previously, it is clear that each of the analyzed vehicles has particular characteristics that directly or indirectly contributed to its success and provided competitive advantages and innovations for the automotive industry. Those differentials were also incorporated and sometimes enhanced by competitors over the past few years.

3.4.2.1 Meriva (GM)

Meriva project was focused on the Brazilian market and was developed in partnership with the German subsidiary, which also had an interest in a similar model aimed at the European market and had the objective of replacing Corsa Station Wagon (AMATUCCI; BERNARDES, 2012). With its first release in August 2002, after a project started in 1999 (AMATUCCI; BERNARDES, 2007), Meriva has innovated in two main aspects: a widely configurable and flexible rear seats and luggage van (AMATUCCI; BERNARDES, 2007; 2012), a limited feature in other vehicles by the age of Meriva. This configuration enables the transition of a space for three passengers to a larger space for two passengers (where the center seat is folded down and becomes a coaster) or also for transporting luggage only, through the folding of all seats (REDETEC, 2003a).

The second differential feature regards the new market segment launched: a modern minivan vehicle with a monoblock structure and high bench height for drivers (AMATUCCI; BERNARDES, 2009a; 2012). Furthermore, the Meriva’s design was the first to be developed and firstly launched in Brazil by GM (AMATUCCI; BERNARDES, 2007).

3.4.2.2 Fox (VW)

VW Fox was launched in 2003 and manufactured at São Jose dos Pinhais in Paraná State in Brazil. It was developed under the PQ24 Platform (VW Polo), aiming to recover sales volume in Brazil (MELLO; MARX, 2007), which was decreasing due to factors such as Polo’s brand idleness and Gol’s life cycle ending (AMATUCCI; BERNARDES, 2009a). Its main distinguishing feature was the “Designed Around the Passengers” concept, which consisted in the prioritisation of the car’s interior design towards a positioning of five passengers comfortably, with all possible practicality spaces and elements to accommodate a whole family, then to design the exterior of the vehicle (CARDOSO; KISTMANN, 2008; AMATUCCI; MARIOTTO, 2012; AMATUCCI; BERNARDES, 2012). Therefore, it is pointed out that this was an important differential aspect since the compact vehicle segment has a high competition level (SANCHEZ et al., 2012).

As result, by the time of their studies, Amatucci and Bernardes (2009a; 2012) reported that VW Fox was the fifth best-selling car in the country, being the second best-selling brand. Besides of that, it has being exported to Europe with the necessary adjustments for product commercialisation and marketing in that region. It is noteworthy that VW Fox has a design more suited to the Brazilian market, i.e. it is not a VW Polo's derivative, but a completely new model (AMATUCCI; BERNARDES, 2012).

3.4.2.3 EcoSport (Ford)

The Ford EcoSport is a vehicle originated from the Ford Fiesta platform and produced at Camaçari in the Bahia Brazilian State. Launched in May 2003 under the name "Amazon project", the automobile started a new market segment (like GM Meriva): the light off-road for urban use (BAZANINI; BERTON, 2011). Zilles (2006) argued that this segment has generated interest not only by its off-road features (appealing for off-road path adventures) but also by the desire to use these vehicles in urban environments. Focused on exterior design, Ford's vehicle sought to meet specific requirements and desires, which were not covered in current cars at the time of its conception. Thus, the compact 'jeep concept' was created, until then non-existent in Brazil. The main focus in the exterior design, dashing and youthful, were characteristics towards a relationship with the environment specifically to meet (by the time of conception) younger public while the internal design was not a priority in the initial model (REDETEC, 2003b). Additionally, the EcoSport had an important goal: recover Ford's capacity and sales volume, which were decreasing at the time of vehicle development (AMATUCCI; MARIOTTO, 2012).

The results of the automaker after launching the vehicle were significant. This it corroborated by the market share increase to 12% by Ford in 2005 and the export of Ford EcoSport to 7 other countries (BAZANINI; BERTON, 2011). The same cited authors state that Ford employees said that besides the exclusivity of EcoSport design, the product appeared as a solution to the product portfolio limitations faced by the carmaker at the time, which brought back consumers, thus contributing to the maintenance of the company's business. Table 3.2 demonstrates the influence of these differences, with annual sales of key models (in an absolute number of vehicles). It is noteworthy noting that despite sales peak occurred in 2004-2005, in 2007 the vehicle was still responsible for 20% of Ford's sales volume, thus demonstrating its strength in automaker's portfolio.

Table 3.2 – Ford's main models of vehicles – Annual sales from 2002 to 2007

Ford Sales – main models	**Jan-Dec. 2007**	**Jan-Dec. 2006**	**Jan-Dec. 2005**	**Jan-Dec. 2004**	**Jan-Dec. 2003**	**Jan-Dec. 2002**
Fiesta	112,504	96,674	99,939	74,259	70,369	66,926
EcoSport	**47,035**	**43,599**	**45,467**	**38,741**	**27,101**	**0**
Ka	29,319	19,840	17,272	22,080	23,561	18,413
Focus	18325	17,854	16,755	17,345	14,771	15,612
Ranger	12,676	9,858	8,537	7,581	5,875	9,653
Fusion	11,416	0	0	0	0	0
% EcoSport	**20**	**23**	**24**	**24**	**19**	**0**

Source: Bazanini and Berton (2011)

3.4.2.4 Sandero (Renault)

The Renault Sandero was launched in 2007 and stood out in its market segment especially because of its three-year extended warranty – until that time nonexistent in the segment. It was based on the Renault Logan platform. Besides, Sandero was the first Renault project directed to Brazilian customers (and also Mercosur customers), considering the local customers' requirements (IBUSUKI et al., 2012). Together with the three-year warranty, the vehicle has more internal space and comfort for five passengers and it targeted cost-effectiveness. Other advantages were visits to selected customers to define the requirements to be considered in design specifications, the recognition of the specialized press as a "Green Car" by the Auto Esporte magazine, incorporating aspects such as low environmental impact in production and emissions level and also high recycling rate (RENAULT, 2010). The high recyclability level is crucial for smaller negative environmental impacts by reducing the raw material demand, energy, and ultimate disposal. In addition, the low impact on production and the reduced emissions is another differentiated Sandero's feature and consistent with the literature. Nunes and Bennett (2008) viewpoint argue that these actions generate contributions regarding the environmental requirements.

In the Paraná State in Brazil, the French executive responsible for the engineering led a workforce whose activity was creating an engineering center next to the industrial units (AMATUCCI; MARIOTTO, 2012). In this context, the Sandero was an initiative of the Brazilian Product Council, which prepared a business plan for the vehicle and sought for technical support in Europe. Thus, it was observed that from the Renault Sandero development experience – together with Spanish and French engineering centers – for the local market (Brazil) and other emerging economies, the Brazilian subsidiary developed a national development team that will have future autonomy to develop further local projects (AMATUCCI; MARIOTTO, 2012).

3.4.2.5 New Uno (Fiat)

Lastly, the most recent of the vehicles studied is described and analyzed. The New Fiat Uno model (2010) is a broad remodeling of a passenger car commercialized for some decades in Brazil. This project had a workforce of 850 engineers and is a result of a "100% Brazilian vehicle" proposal, i.e. all phases, from design and product concept definition to production processes were carried out in the country, with an investment of US$ 150 million (IBUSUKI et al., 2012). One of the vehicle's differentials occurred during product development itself: a wide research was conducted in real time with groups of customers in different regions of Brazil simultaneously to the new product development phases. This research was within the scope of open innovation. This action contributed to the design of an automobile which was strongly suited to customers' needs and desires like modernity and high level of customization.

Yet within this aspect, literature points out the importance of the closer contacts with customers during NPD, thereby corroborating the relevance of the actions conducted in the New Fiat Uno. This importance relies on the fact that the company can be able to develop solutions to customer needs such information will probably contribute to the development of more appropriate solutions (GONZÁLEZ; TOLEDO, 2012). Hence, the integration and engagement to the customers are significant, because usually, their actual needs are implicit, being difficult to be expressed mainly by conventional market research methods (GRIFFIN et al., 2009).

Finally, it is noted that all investigated vehicles provided contributions to the Brazilian automotive industry as well as generated learning at a global level to OEMs through distinct competitive advantages.

3.5 CONCLUDING REMARKS OF THIS CHAPTER

The study identified and analyzed common and specific characteristics regarding vehicle development in Brazil in order to find out the main factors that contributed to the process and potentially brought innovation and competitive advantages to OEMs. Through literature on the topic, it was possible to identify features that have been relevant to emerging markets. Note that all investigated vehicles contributed in their market segments, from launching a new segment itself (such as GM Meriva and Ford EcoSport) to a complete redesign and product customization (New Fiat Uno). Yet in the strategic context, the adoption of modularity in design, production and use was important to bring benefits such as component and parts sharing, platform reuse, costs reduction, increasing interaction with suppliers and higher customization level. Thus, it was noticed that modularity emerges as an important feature to competitive vehicle projects.

From the particular features identified, firstly it was noted that all differential was generated through aspects which were not explored in the market by the time the vehicle was launched. Those include launching a new market segment (GM Meriva and Ford EcoSport), more internal space for passengers (VW Fox), three-year warranty (Renault Sandero) and high customization (New Fiat Uno). These new segments are strongly connected with local customers' specific requirements. Some automakers still have centralized activities in their respective headquarters, while some of them are considering establishing or planning R&D centers in Brazil towards a higher proximity to local potential customers and consumers, such as Hyundai and certain Chinese companies. Hence, it is possible to infer that these specific characteristics were the most relevant in NPD inside Brazil because they were the main innovation agents.

Limitations of this study regard the lack of information about improvements and adjustments made to the five vehicles over the years since the scope of this work considered only the first versions of each analyzed project. Nevertheless, this emerges as an opportunity for future studies. In addition, it is intended to broaden the study through a specific investigation of popular cars, which are most preferred in Brazil. Moreover, it can be done in-depth studies of each of the five vehicles described along with other recent projects, by collecting field data in the respective OEMs.

Finally, an investigation regarding modularity and its influence on competitive advantages is to be conducted, targeting the concepts and relationships among modularity typologies (design, production, organizational and use) and how it contributes to vehicle development. Thus, the next chapter approaches the literature review and analysis regarding modularity in the industrial context, prior to investigate the modular strategy in the auto industry.

4 MODULARITY CONCEPTS, TYPOLOGIES, AND PRINCIPAL DOMAINS: A LITERATURE REVIEW AND ANALYSIS

This chapter presents the contents of the first article[14], which developed an analysis of publications regarding modularity and their applications in the industrial and organizational perspectives, towards a concept better understanding and context where it is applied. At the end of this chapter, the thesis expects to provide a general scenario of modularity concepts and applications according to its typologies and industrial contexts.

4.1 MODULARITY ORIGINS, CONCEPTS, AND APPLICATIONS

Modularity concept has been widely utilized since the beginning of the 21st Century. However, the concept emerged before, in the 1960's within the computer industry, bringing competitive benefits and demonstrating significant importance in the product development process (ARNHEITER; HARREN, 2006). Besides, modularity helps designers and engineers in the development of products which have potential to comply with different markets (CARDOSO; KISTMANN, 2008). During the past years, companies are increasingly forced to optimize their resources, adapt themselves to the global market dynamics and satisfy consumers and customers, which are getting more demanding due to a broad access to information. In this context, one of the strategies that help to improve product and process quality is modularity, which aims to (BALDWIN; CLARK, 2004; CARNEVALLI et al., 2011): facilitate the management of complex products and processes through the division into simpler modules; enable parallel production activities, since modules can be manufactured simultaneously and; adapt production to future uncertainties, because the final product might be modified by adjustment of a single module or component, requiring a lower cost than redo the whole product.

As mentioned before, modular products are designed as a set of independent and simpler modules, which can be reused and interchanged to maximize product variety (STARR, 1965). Thus, modular products support standardization that facilitates (re)manufacturing, helps to eliminate waste and decrease costs. In addition, modularity is an attribute

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[14] CORRÊA, L.A.; KUBOTA, F.I.; CAUCHICK MIGUEL, P.A. Towards a contribution to modularity concepts and principal domains. **Product: Management & Development**, v. 10, n. 2, p. 119-130, 2012.

of a complex system that advocates designing structures based on reducing interdependence between modules and maximizing interdependence within them that can be mixed and matched in order to obtain new configurations without loss of functionality or performance in the system (LANGLOIS, 1992; BALDWIN; CLARK, 1997; CAMPAGNOLO; CAMUFFO, 2010). In other words, modularity has many facets starting with interchangeability of parts (STARR, 2010). According to the previous author, modularity varieties stem from different concept applications of units of interchangeability.

During the last decade, modularity attracted the attention of numerous management scholars (CAMPAGNOLO; CAMUFFO, 2010). In addition, authors have been studied the subject in several perspectives: product modularity (CARIDI et al., 2012; HUANG et al., 2012; LAU et al., 2011), process modularity (PARENTE et al., 2011; JACOBS et al., 2011), service modularity (GEUM et al., 2012; LIN; PEKKARINEN, 2011; BASK et al., 2011) and/or production modularity (RODRIGUES et al., 2009; DORAN et al., 2007), as well as the impact on the final products quality (LAU et al., 2009), critical factors in the modular product management (LAU et al., 2010) and competitive advantages through the modular strategy adoption (JACOBS et al., 2007).

However, although modularity has been a popular concept especially in operations research and management for decades, no universal definition of modularity seems to exist (BASK et al., 2010). Therefore, the objective of this chapter is to examine systematically studies about modularity and its applications in the industrial and organizational context, dealing with different facets of modularity. Relevant concepts were identified and discussed. An initial conceptual framework highlighting the modularity concept is derived based on this literature analysis. The remainder of this chapter is structured as follows: Section 4.2 presents the research method. Section 4.3 provides the theoretical basis on modularity by expressing its main concepts and types of modularity (used for literature classification). Section 4.4 presents the research issues on modularity including findings from the literature review and finally, section 4.5 draws some concluding remarks and main implications of this work as well as the next steps of this research project.

4.2 RESEARCH METHODS

This paper is classified as a theoretical study (according to BERTO; NAKANO, 2000; CAUCHICK MIGUEL, 2010) based on a systematic literature review. It is essential to any research proposal that the subject is defined and understood, which involves identifying the current theoretical state of the art. Moreover, the objective of a literature study is not merely to group authors and publications. In fact, main purposes include the identification of gaps in the literature as well as dominant research methodologies associated with the chosen research subject.

In this sense, this paper employs a systematic literature review, firstly using key works in databases such as ISI Web of Knowledge, Scopus, Compendex and SciELO to retrieve articles regarding the topic "modularity". After that, each article was examined in order to identify main aspects that involve modularity (i.e. the main issues discussed in the article), industrial sector, and taxonomy related to modularity. It is worth stressing that this paper does not describe the contents of each examined paper. Nevertheless, the concept of the studied subject (i.e. modularity) is outlined as well as its types aiming to identify important issues concerning the taxonomy. The bibliographical sources that were used in this paper are mainly publications in leading referred journals.

A literature review can be categorized according to the following criteria (NORONHA; FERREIRA, 2000): purpose (analytical or supportive – suitable to the thesis, dissertations, etc.), scope (thematic or time-based), function (historical or for updating), and approach (critical or bibliographical). Table 4.1 shows how this paper is categorized according to the previous criteria in addition to the rationale for this classification.

Publications of interest were identified and retrieved from various data bases, e.g. ISI, Emerald, SciELO (Scientific Electronic Library Online), etc. A software (EndNote® X5) was used to record and organize the references. Each article was individually and electronically recorded for further analysis.

Table 4.1 – Classification of the literature review in this paper.

Classification	Type	Definition	Rationale
Purpose	Analytical	Proposes a group of various issues in a subject and specifically chosen topic	Identify existing publications of taxonomy on modularity
Scope	Thematic	Presents a specific and in-depth description about a chosen topic	Identify the state of the art of current modularity theory
Function	For updating	Describes most relevant literature recently published development of knowledge	Identify most publications that deal with modularity concepts
Approach	Critical	Provides a reflection on the chosen topic	Establish a theoretical map concerning issues on taxonomy

Source: developed by the authors based on Noronha and Ferreira (2000)

4.3 MODULARITY – TERMS AND DEFINITIONS OF A MULTI-CONCEPT

The term modularity is familiar to industry and academia, but often is not clearly understood because of its broad interpretation (TSAI; WANG, 1999). In fact, there are a number of terms that is used to describe modularity, showed in Table 4.2.

There are several modularity definitions in literature (ULRICH, 1995), thus it can be considered as a multifaceted concept (BALDWIN; CLARK, 2000). Even the definition of modularity is in question (GERSHENSON et al., 2003). A major reason for this problem is that modularity definitions come in different perspectives (FIXSON, 2005) and heterogeneity stymies systemization (STARR, 2010). Starr (2010) put forward that modularity, in spite of its age, is a splintered concept with a variety of inchoate offshoots (certainly not well-organized). The author says that splintering occurred slowly but surely as (over almost 50 years) a great number of constituencies defined and applied modularity to their own spheres of interest.

Table 4.2 − Terms on Modularity.

Terms	References
Modular components	Sanchez and Mahoney (1996); Shaefer (1999)
Modular innovation	Henderson and Clark (1990); Christensen and Rosenbloom (1995); Hsuan (1999)
Modular product architecture	Ulrich and Eppinger (1995); Sanchez and Mahoney (1996); Lundqvist et al. (1996)
Modular system	Langlois and Robertson (1992); Baldwin and Clark (1997)

Source: constructed based on Mikkola (2001a)

Another reason that may influence on the difficulties to define a generic concept of modularity is because there has been little effort made to reach a consensus on the definition of this term and its appropriate use (GERSHENSON et al., 2003). This state of affairs is shocking because when first elucidated, the modularity concept seemed to be simple and straightforward (STARR, 2010). In addition, Campagnolo and Camuffo (2010) stated that modularity broad-based appeal has generated some controversies and ambiguities on how modularity should be defined, measured and used in managerially meaningful ways. In their study, they found that this ambiguity impedes rigorous empirical studies capable of understanding the relationship between modularity in product, in production and in organization design. Nevertheless, successful applications exist. Some of those aspects are discussed next.

4.3.1 The concept of modularity

For human beings, the only way to manage a complex system or solve a complex problem is to break it up (BALDWIN; CLARK, 2000). Modularity is an approach for organizing complex products and process efficiently (BALDWIN; CLARK, 1997) by decomposing complex tasks into simpler portions so they can be managed independently (MIKKOLA, 2001b). Modularity should also be defined as interchangeability of alternative substitutable parts or materials of a product (STARR, 2010). The development of interchangeability and standardization of parts were in many ways the precursors to modularity (ARNHEITER; HARREN, 2006). In this sense, modularity arises from the decomposition of a product into subassemblies and components (GERSHENSON et al., 2003). In the literature, two different emphases when defining modularity (see Table 4.3) are frequently used (BALDWIN; CLARK, 1997; ULRICH, 1995; ULRICH; TUNG, 1991).

Table 4.3 – Emphasis of most cited modularity concepts.

Emphasis	**Publications**	**Sector (product) where the concept was applied**
Physical structure (Baldwin and Clark, 1997)	Doran (2003; 2004; 2005)	Automotive (Supply chain)
	Fredriksson (2006)	Automotive (Modular assembly processes)
	Blecker and Abdelkafi (2005)	Personal Computer (PC)
	Bask *et al.* (2010)	Logistics Services
	Jose and Tollenaere (2005)	Different products families (design using platform concept)
	Caridi *et al.* (2012)	Furniture industry
	Asan *et al.* (2004)	Electronic Products (Domestic gas detector product family)
	Miozzo and Grimshaw (2005)	Information Technology Outsourcing
	Voordijk *et al.* (2006)	Construction industry
Function (Ulrich and Tung, 1991; Ulrich, 1995)	Fredriksson (2006)	Automotive (Modular assembly processes)
	Blecker and Abdelkafi (2005)	Personal Computer (PC)
	Jiao and Tseng (2000)	Electronic products (*e.g.* as telephone switching PBX, stereo equipment, computers, and instrumentation)
	Bask *et al.* (2010)	Logistics Services
	Lau *et al.* (2007)	Supply Chain Management in Manufacturing Industry
	Jose and Tollenaere (2005)	Different products families (design using platform concept)
	Brusoni and Prencipe (2001)	Aircraft Engine and Chemical Engineering

Ulrich and Tung (1991) and Ulrich (1995) definitions are that modularity is the relationship between a product’s functional and physical structures such that there is a one-to-one or many-to-one correspondence between the functional and physical structures and unintended interactions between modules are minimized. These definitions were built in different applications of the concept. The authors (ULRICH, 1995; ULRICH; TUNG, 1991) were in the context of product architectures and based on the relationships between the function and physical structures. In their work, Baldwin and Clark (2000) particularly focus on products and processes and they state that it is difficult to establish a definition of modularity on function, which is inherently manifold and non-stationary. Therefore, Baldwin and Clark's (1997) definition of modularity is based on relationships among physical structures, not functions. Hence, Baldwin and Clark (1997) define modularity as building a complex product or process from smaller subsystems that can be designed independently yet function together as a whole.

In fact, more than 10 years ago, the majority of modularity studies was related to functional modularity (SIDDIQUE; ROSEN, 1998) and in recent years is still in this way. There is a clear consensus on the point of form and function independence (GERSHENSON et al., 2003). On the words of Gershenson et al. (2003) the roots of modularity definitely lie in the form-function relationship and most publications treat it as such. By analyzing Table 4.1, it is not possible to draw a conclusion on the most suitable definition of modularity for an industrial sector or product. Some authors such as Fredriksson (2006), Blecker and Abdelkafi (2005), Bask et al. (2010) or Jose and Tollenaere (2005) use both definitions to support their work despite the differences among the industrial sectors studied. However, when a publication deals with modular product development, Ulrich (1995) and Ulrich and Tung (1991) definition are commonly adopted as it can be observed in the Jiao and Tseng (2000) study.

Besides the definition of modularity based on form and/or function, some other definitions look on the term "independence" as fundamental. Independence and functional independence have dominated the modularity discussions and the element of independence is at the core of the intent in modular design (GERSHENSON et al., 2003). Chen et al. (1994) propose modularity based upon the 'relationship between achieving functional independence and reducing the interactions between modules'. Modularity in general aims at packaging individual functionalities in a way that functionalities in one module would have as much in common as possible and that those modules would be as reusable as possible (TSAI; WANG, 1999). The functional independence significance is that it can facilitate the extension and configuration of modules. This is very important for the product family development. The principle of functional independence implies that there should be ideally a one-to-one mapping between sub-functions and modules (ULRICH, 1995).

Bask et al. (2010) present their own summary of the literature review, defining a modular system as a system built of components, where the structure of the system, functions of components and relations of the components can be described so that the system is replicable, the components are replaceable, and the system is manageable. Others authors use the benefits or the usability to define the term. In the past, modularity was defined by Walz (1980) as constructed of standardized units of dimensions for flexibility and variety in use. Therefore, broadly defined, modularity is the use of modules to facilitate assembly and customized configuration of finished products, it can be used to simplify and facilitate the design of production systems as well as products (ARNHEITER; HARREN, 2006; CARIDI et al., 2012). Huang and Kusiak (1998) refer to modularity as the use of common units to create product variants. It can be defined as using sets of units designed to be arranged or joined in a variety of ways (CIVIL ENGINEERING RESEARCH FOUNDATION, 1996).

Modularity is also a concept present in other knowledge fields. In software design, modularity usually refers to “tools for the user to build large programs out of pieces” (CHEN, 1987). Modularity in art has been defined by Jabblan (1997) as the use of several basic modules for constructing a large collection of different structures. An example would be bricks in architecture or in ornamental brickwork. The author states that modularity principle is a universal economy of nature principle, which allows diversity and variability from a combination of a few basic elements. Schilling (2003) considers modularity in the general case without restrictions concerning the kind of system, defining modularity as a general systems concept: it is a continuum describing the degree to which a system’s components can be separated and recombined, and it refers both to the tightness of coupling between components and the degree to which the “rules” of the system architecture enable (or prohibit) the mixing and matching of components. Blecker and Abdelkafi (2006) for the purpose of their work, where the subject was "complexity and variety in mass customization system", define modularity as an attribute of the product system that characterizes the ability to mix and match independent and interchangeable product building blocks with standardized interfaces in order to create product variants. The objective of mapping between functional elements and physical building blocks is preferable and refers to an extreme and ideal form of modularity.

Within all those definitions, they just account for modularity form, function, independence, usability or benefits. However, with the growing environmental pressure, the definition must be extended beyond all these concerns across the product life-cycle and the benefits that modularity can achieve with it. A term that comes with product life-cycle is similar. For example, Gershenson et al. (1999) define life-cycle modularity as modules and interactions that arise from the various processes the components undergo during their life-cycle including development, testing, manufacturing, assembly, packaging, shipping, service, retirement, and so on. Newcomb et al. (1996) study is based on their hypotheses that product architecture is the governing force in life-cycle design and that more modularity is better in all life-cycle viewpoints.

As can be seen, there is not a clear consensus on the definition of modularity and the publications usually use the term pointing to the type of work. Nevertheless, in order to enhance the understanding of modularity, it is necessary to define what a module is.

4.3.2 Module definition

A module is a unit whose structural elements are powerfully connected among themselves and relatively weakly connected to elements in other units as quoted by Baldwin and Clark (2000). Also, a module is described as a set of components (Newcomb et al., 1996). One can think of a module as a self-contained subassembly that connects to other modules using common interfaces (ARNHEITER; HARREN, 2006). Clearly, there are degrees of connection, thus there are graduations of modularity (BALDWIN; CLARK, 2000). As defined by Allen and Carlson-Skalak (1998) a module is a component or group of components that can be removed from the product non-destructively as a unit, which provides a unique basic function necessary for the product to operate as desired. Going into more details, Marshall et al. (1998) describe modules as having the following characteristics:

- They are co-operative subsystems that form products, manufacturing systems, and so on;
- Functional interactions occur within rather than between modules;
- They have one or more well-defined functions that can be tested in isolation from the system and are a composite of components of the module;

- They are independent and self-contained and can be combined and configured with other modules to achieve overall function.

Modules can include a wide range of value-added content and complexity ranging from simple and disposable modules such as ballpoint pen refills to larger complex modules like automobile chassis. By increasing the size and complexity of each module, it is possible to greatly simplify the supply network by reducing a product containing thousands of individual parts to a handful of subassemblies (ARNHEITER; HARREN, 2006). In an ideal module, each component is independent of all components not contained in that module throughout the entire product life-cycle (independence). In addition, each component in the module is processed in a similar manner during each life-cycle stage (similarity) (GERSHENSON; PRASAD, 1997).

4.3.3 Modularity principal domains

As mentioned earlier, modularity can be considered as a multifaceted concept (BALDWIN; CLARK, 2000) and modularity definitions come in different perspectives (FIXSON, 2005). Hence, literature usually groups modularity concept in four principal domains, namely: modularity in design, modularity in production, and modularity in organization (SAKO; MURRAY, 2000; CAMUFFO, 2001; DORAN, 2003) or modularity in organization and supply chain (BASK et al., 2010). In addition, other authors also consider modularity in use (SAKO; MURRAY, 2000; CARDOSO; KISTMANN, 2008; PANDREMENOS et al., 2009) and modularity in services (BASK et al., 2010; GEUM et al., 2012).

4.3.3.1 Modularity in design

Modularity in design has been investigated to reduce design process complexity (ULRICH; EPPINGER, 1995; FUJITA, 2002). Modularity in design can be, therefore, defined as choosing the design boundaries of a product and its components, i.e. on how to divide a system into modules, so that the design features and tasks are interdependent within and independent accross modules (HUANG; KUSIAK, 1998; CAMUFFO, 2001).

Ulrich (1995) analyzed the structures of design, in terms of product structure, physical functions, etc. and distinguished them into modular architecture and integral architecture. According to Fujita (2002), the former indicates a one-to-one mapping from functional elements in a function structure to physical components of a product and decoupled interfaces among components. The latter indicates a complex (not one-to-one) mapping functional elements to physical components and/or coupled interfaces between components. An important task in product architecture is to find common modules across products for "platforming" a product family or to find a common module for joint development with a partner. The authors (Fujita, 2002) developed a five-step algorithm to group functions into modules and choose from different candidates to form a good platform. The algorithm accomplishes this task of grouping and creating a dendrogram which is applied to a group of four products. Aiming to provide a taxonomy on modularity, Bi and Zhang (2001) state that there are two basic categories of activities involved in modularity design:

Product modularity: it should result in an architecture of a product such that the product can be made by simply assembling pre-existing components. To realize it, product functions, product life cycle issues and costs should be considered;

Task-oriented determination of modular configuration: it is described by Liang and O'Grady (1998) as: 'given a set of candidates modules, produce a design that is composed of a subset of the candidate modules and which satisfies both a set of functional requirements and a set of constraints'.

Bi and Zhang (2001) provide more details on those categories by deploying them in issues showed in Table 4.4. The authors also state that both product modularity and determination of modular configuration involve design evaluation, which can be performed from different viewpoints: function, flexibility, cost-effect, environment, technique, and complexity.

Table 4.4 − Issues in design modularity.

Product modularity	**Modular configuration determination**
Identification of requirements	Architecture and requirements description
Determination of modular architecture	Determination of a sub-problem
Module design	Constraints and objectives coordination
	Determination of interfaces and internal variables

Source: constructed based on Bi and Zhang (2001)

Automotive firms, for instance, usually employ modularity in design. Fredriksson (2002) cites Mercer (1995) and McAlinden et al. (1999) to exemplify that typical car modules on the highest level in the product structure are: seats, cockpits, front-ends, headliners, door panels, fuel tanks, etc., which all contain variant specific components.

4.3.3.2 Modularity in production

Modularity in production means choosing plant design boundaries to facilitate both manufacturing and assembly to meet product variety, production flow, cost and quality requirements (CAMUFFO, 2001). In this direction, there are now commercial equipment for enabling and facilitating the introduction of modular plants. A ‘component-based automation’ solution is supplied to a modular plant at VW in Wolfsburg, Germany (SIEMENS, 2004). It is a solution for the factory paint shop; a decentralized automation approach in which intelligence is distributed to technological modules that combine logically mechanics, electrical functions, and control program. The technological modules include robots, filling machines and other parts of a production plant (SIEMENS, 2004).

In addition, modularity in production also refers to apply sub-assembly, pre-fitment testing of modules and transferring some of these activities to suppliers (DORAN, 2003). The influence of modularization on the factory floor lies in the ability to pre-combine a large number of components into modules and for these modules to be assembled off-line and then brought onto the main assembly line and incorporated through a small and simple series of tasks (SAKO; MURRAY, 2000). In this sense, Fredriksson (2002) analyses the conditions provided for module assembly units performance through a case study conducted at Volvo. It considers pre-assembly and outsourcing. The paper also shows that organizational forms (ownership and location) provide different conditions for module assembly units performance. The modularity in organization is further discussed in the next section.

For example, many automakers such as GM, Fiat, Ford, Daimler-Chrysler, Mercedes-Benz, and VW have experienced with modular assembly plants in the past years (CAMUFFO, 2001). Volkswagen was the first plant to apply modularity concepts extensively, specifically at its plants in Resende in Brazil, Boleslav in the Czech Republic and Mosel in Germany (MARX et al., 1997). Ford and GM have built new plants that specifically accommodate modular assembly (DORAN, 2003).

4.3.3.3 Modularity in organization

Modularity in organization relates to the organizational process, governance structures and contracting procedures that are adopted or used to accommodate modular production at both the intra and inter-firm context (DORAN, 2003). For instance, Camuffo (2001) presents a case study of the roll-out of a Fiat world car in a field work carried out in 6 countries. In this study, the author examined aspects of modularity, outsourcing, and globalization to find out if there were a relationship among them. The case study pointed out that, at the firm level, those concepts are linked. Outsourcing and modularity, though increasingly inseparable and overlapped in practice, remain conceptually distinct (CAMUFFO, 2001).

4.3.3.4 Modularity in use

Modularity in use is a consumer driven decomposition of a product with a view to satisfying the ease of use and individuality (PANDREMENOS et al., 2009). The authors also mention that the latter is intimately connected to the concept of mass customization. This modularity approach is strongly linked with modularity in design (product architecture) since it allows different component combinations to provide variety to attend customers' needs and expectations with agility and quickness (SAKO; MURRAY, 2000; CARDOSO; KISTMANN, 2008).

4.4 MODULARITY IN THE AUTOMOTIVE INDUSTRY − CONCEPTS, BENEFITS AND DIFFICULTIES

Modularity is present in a variety of industries, such as electronic components (as cameras or computers) and especially the automotive sector has been applying the modular strategy in its products and processes (ARNHEITER; HARREN, 2006; SALERNO et al., 2009). It is clear that with the automotive sector high growth and consequently increase in production and consumption of vehicles in Brazil and worldwide, the competition among OEMs has increased considerably, which generates a crescent need for competitive advantages and attractive requirements to customers and consumers. According to Pandremenos et al. (2009), automotive OEMs usually consider modules as a collection of components, physically close to each other that are both assembled and tested outer facilities and can be assembled very basically onto the vehicle.

In the automotive sector, Baldwin and Clark (2000) and Morris and Donnelly (2006) say that there are usually two modularity approaches: product modularity and production modularity. In other words, Pandremenos et al. (2009) classify two types of modularity in the sector:

- Level-1 or assembly modules, which is the practice of shifting sub-assembly lines that manufacture modules next to the final vehicle assembly line to separate supplier facilities at some distance from the plant and no radical change in the design of the module is affected, and;
- Level-2 or design modules, which are modules that are optimized at the final assembly level by independent suppliers.

However, another modularity approach has been used in the sector: the modularity in use, which considers the customer's needs and customization characteristics regarding the product (CARDOSO; KISTMANN, 2008; PANDREMENOS et al., 2009). This latter modularity approach is used to add value to the final product, as a way to satisfy customers' needs, since the production modularity objective is to improve production performance and efficiency, but not always complying with consumers' requirements (CARNEVALLI et al., 2011).

According to some authors, modularity brings the following benefits:

- Complexity reduction of product specifications and activities (POLITZE et al., 2012; CHRISTENSEN, 2011; CAUCHICK MIGUEL et al., 2009), by specifications' partition through the product developed modules. It facilitates comprehension about the product architecture, turning specifications more simple and enlightening;
- Product development time reduction (ZIRPOLI; BECKER, 2011a; 2011b; CARNEVALLI et al., 2011; JACOBS et al., 2007), which optimizes lead-time and contributes to the application of concurrent engineering principles;
- More specialized suppliers (ZIRPOLI; BECKER, 2011b; MONDRAGON et al., 2009), since the division of modules force suppliers specialize themselves to provide the best solution in their components, potentially facilitating innovation and competitive advantages for both suppliers and OEMs (Original Equipment Manufacturers);

- Suppliers in a higher level of maturity regarding modularity have more potential to add value for the OEMs and their business, through constant creation of competitive advantage, contribution, and commitment for product customization (PRIETO; CAUCHICK MIGUEL, 2011). This benefit can also enable long-term contracts and a closer relationship between OEMs and suppliers.

However, modularity also brings some disadvantages and difficulties:

- Loss of control in product development activities by the OEMs (ZIRPOLI; BECKER, 2011a; 2011b), since the responsibility transfer to suppliers, make them more autonomous. Carnevalli et al. (2011) corroborates, saying that suppliers make more decisions about product design because they become the main modules' responsible;
- Increased supplier dependence by OEMs (RODRIGUES et al., 2012; ZIRPOLI; BECKER, 2011a; 2011b; CARNEVALLI et al., 2011): this dependence can bring problems in OEMs' organizational and production processes, which can affect the OEM/suppliers relationship. In addition, many defined specifications will only be observed and tested after assembling the components, which can generate high costs (even recalls, depending on the case) in case of non-compliance and/or inconsistency in the complete assembled product;
- The same dependence related above, but in reverse: suppliers can become overly dependent on automakers, which can have complete design control (CERRA et al., 2011; MELLO; MARX, 2007). Besides, OEMs can define the suppliers' participation degree on projects (SALERNO et al., 2009). This action can generate considerable restrictions and minimal influence on modules development by the suppliers, complicating the search for components innovation;

The literature on modularity describes different approaches within the world. For example, Pandremenos et al. (2009) and Carnevalli et al. (2011) say that in Western and Japanese auto industries have been following dissimilar ways in implementing modularity: the latter has preferred the adoption of modularity in design, while the first considers more modularity in production. Hence, these differences might contribute to the lack of consensus towards a unique modularity concept. In the following section, a literature summary on modularity is presented.

4.5 LITERATURE SUMMARY ON MODULARITY

After examining studies regarding modularity and its various approaches (such as modularity in design, production, and use), it is possible to point out some recommendations and features for the adoption of modularity according to the literature. Firstly, modular products manufacturers may develop stronger communication among module development teams (LAU et al., 2011), aiming to improve the definition of responsibilities as well as the relationship between companies. In this sense, there is an additional need of efforts towards a better coordination and management of modular components (MIKKOLA, 2007), since this additional endeavor might contribute in minimizing tolerance management issues, maintain components standardized (PANDREMENOS et al., 2009).

Regarding production modularity, the means of modularization on the factory floor is the ability to pre-combine a large number of components into modules and these modules to be assembled off-line and then brought onto the main assembly line to be incorporated into a small and simple series of tasks (SAKO; MURRAY, 1999). Paralikas et al. (2011) argue that agility is necessary to product all available modular product variants quickly, to better attend consumers' needs and expectations and lower costs to enable it, simultaneously.

Nevertheless, although literature affirms that there is not a consensus (for example, GERSHENSON et al., 2003), it seems to have an agreement regarding modularity: every system is modular to some extent: very few systems are composed of parts that interact and affect each other so tightly that there is no opportunity to mix-and-match the subsystems they are made of (CAMPAGNOLO; CAMUFFO, 2010). Mello and Marx (2007) study corroborates, stating that rarely a product is only integral or modular; a product is classified in relation to other products according to its modularity degree. The next section will point out the main conclusions regarding this study.

4.6 CONCLUDING REMARKS OF THIS CHAPTER

This chapter aimed to systematically examine studies about modularity and its applications in the industrial and organizational context, dealing with different modularity facets. The interest on modularity is becoming ascendant. Perhaps may not be necessary become within a generic and accepted definition to continue the evolution and comprehension of modularity theory. On the other hand if consolidated it can potentially affect it in a positive manner. Varieties of modularity stem from different applications of the concept and each application carry on a specific perspective. However, some terms have to be remembered when dealing with modularity, such as: “form”, “function”, “interchangeability”, “independence” and “similarity”. The module concept is well understood by the literature, although it has broad interpretations according to each approach (design, production, use, service and/or organizational). The different modularity domains are extremely connected among themselves and one of them, i.e. modularity in design, normally guide the others.

In this context, modularity in design, where functional perspective is more utilized, is the most prominent approach, followed by production modularity, where the division of physical component is priority in order to reduce operational costs and support better production line, and modularity in use, which addresses customization features in order to meet customer expectations. Besides these three approaches, studies have been conducted on service modularity, aiming to organize elements and requirements of intangible processes in a modular way (grouping these characteristics "module-by-module"), and organizational modularity, which deals with the definitions towards managerial processes modularization to improve definitions in managerial activities and tasks among organizations or within a company itself. In addition, there is a trend to maintain the lack of consensus regarding a universal modularity concept due to different approaches used, as previously discussed. For example, modularity in design usually refers to product functionality, an aspect that is not essential if applied in the production process as well as modularity in use may not be the best approach to managerial processes, and so on.

Further research should investigate a better understanding about variations of modularity concept, trying to find what characteristics are predominant throughout all concept variants (design, production, use, organizational, etc.). Another opportunity is to investigate variants of modularity concept as well as the influence of these variations among industrial sectors that often use the concept, such as automotive, electronics, furniture, etc. In addition, as mentioned previously, this chapter shows that MID is the most explored approach, followed by MIP. In this sense, the next chapter presents a literature analysis on MID in the automotive industry (the most highlighted sector in terms of modularity application).

5 DESIGN MODULARITY: BENEFITS AND DRAWBACKS ANALYSIS THROUGH A LITERATURE REVIEW IN THE AUTOMOTIVE AND SUPPLIERS PERSPECTIVE

The following chapter presents the contents published in the second article[15]. It shows a literature review on modularity focused on the design modularity within the automotive industry. Publications were retrieved in peer-reviewed journals in major databases. The search identified one 123 articles, from which 45 were suitable for content analysis. Conclusively, benefits of modularity in design have been more exposed in the literature compared to the difficulties in the context of the automotive sector. It is observed that OEMs have more benefits than suppliers do since the latter have more difficulties to adapt their organizational and productive processes towards design modularity.

5.1 CONTEXT: MODULARITY STRATEGY IN THE AUTOMOTIVE INDUSTRY

Differentiated and innovative products have been increasingly desired and demanded by customers, who have become more discerning in their purchasing decisions. In areas where competitiveness is more intense, a creation of a differentiated product provides possibilities to the companies to be in the market.

One of the strategies that help to improve products and processes is modularity, which aims to (BALDWIN; CLARK, 2004; CARNEVALLI et al., 2011): facilitate the management of complex products and processes through the division into simpler modules; enable parallel production activities, since modules can be manufactured simultaneously and; adapt production to future uncertainties, because the final product might be modified by adjustment of a single module or component, requiring a lower cost than redo the whole product (CORRÊA et al., 2012). The concept of modularity is present in a variety of industries such as electronic, computing as well as the automotive sector. Those industrial sectors apply the modular strategy in their products and processes (ARNHEITER; HARREN, 2006; SALERNO et al., 2009). Moreover, it is clear that with the automotive sector growth

[15] KUBOTA, F.I.; GONTIJO, L.A.; CAUCHICK MIGUEL, P.A. Design modularity: identification of benefits and difficulties through a bibliographical analysis in the perspective of automotive assemblers and suppliers. **Product: Management & Development**, v. 11, n. 1, p. 24-32, 2013.

and a consequent increase in vehicles' production and consumption in Brazil and worldwide, there has been a high increase in competition among automobile organizations.

In this context, series of decisions need to be taken into consideration to apply modularity in vehicle design, which demonstrates the complexity of this strategy (ASAN et al., 2004). Like other strategies and methods, decisions about the design modularity degree and the choice of production processes significantly affect project development costs of cars. In this sense, this study conducts a review and a preliminary organization of the literature regarding the benefits and difficulties of design modularity in the automotive industry. One of its purposes is to offer a broad overview of this strategy for vehicle development. This work is part of a major research project on modularity, which previous results were published earlier (CAUCHICK MIGUEL, 2004; 2005; CAUCHICK MIGUEL et al., 2009; CAUCHICK MIGUEL; HSUAN, 2010; CARNEVALLI et al., 2011; RODRIGUES et al., 2009; 2012; CORRÊA et al., 2012).

To fulfill this objective the paper is structured as follows. After this introduction, section 2 presents a theoretical framework about modularity concepts with the emphasis on design modularity. Section 3 describes the research methods followed by the presentation and discussion of the results in section 4. Finally, section 5 draws the conclusions and suggests issues for future research.

5.2 MODULARITY CONCEPTS AND DEFINITIONS

During the 1960s, modularity emerged in the computer industry, generating competitive advantage and demonstrating significant importance in the product development process (ARNHEITER; HARREN, 2006). The modular strategy consists in decomposing complex products in subsystems that are complete functional units, which can be designed and manufactured independently (which enables the construction of different products through subsystems combination), but with an integrated operation (BALDWIN; CLARK, 1997; PERSSON, 2006).

Morris and Donnelly (2006) distinguish two types of modularity: design – or product - and production. The authors firstly define modularity in design, which is focused on the boundaries among subsystems integrated components within design features and tasks. In addition, Graziadio (2004) states that modularity in design aims at reducing lead-time by doing different activities simultaneously. She adds that the adoption of this kind of modularity provides modules designed by specialized suppliers in a given category, which contributes to technological improvements.

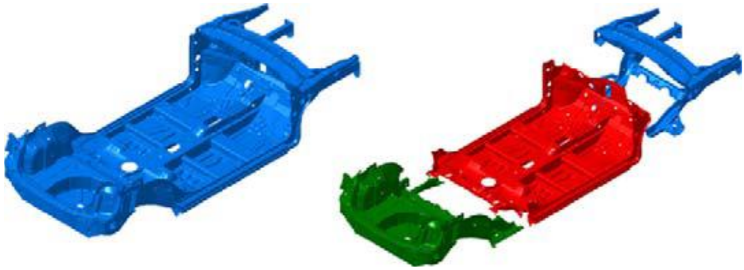
Modular production enhances the final assembly of the product, allowing the occurrence of variability without increasing costs (SILVA; CAUCHICK MIGUEL, 2006). Stäblein et al. (2011) complement this argument by saying that sharing modules and combine them in different versions expand product variety. The modularity in design is detailed next since is the focus of this paper.

5.2.1 Design modularity

Design modularity may be the most important factor to determine the product architecture configuration (ULRICH; EPPINGER, 2000). Mikkola and Gassmann (2003) corroborate this argument by citing that products with a high level of modularity allow high product variants by mixing and matching the product modules, while products with low modularity allow optimization of components for a particular product. Modularity helps in the development of products that have the possibility of meeting different markets (CARDOSO; KISTMANN, 2008). It is a concept used since the beginning of the century, however, its use in design is a current trend not only in technology but also in the industry in general (SILVA; CAUCHICK MIGUEL, 2006). Moreover, product modularity has been targeted as a way to accelerate new product development and reduce costs in this process (JACOBS et al., 2011).

Concerning product/design modularity, Morris et al. (2004) state that it is focused on the boundaries among integrated components subsystems within design features and tasks, which should be interdependent modules (CAUCHICK MIGUEL, 2004). Graziadio (2004) and Cauchick Miguel et al. (2009) add that such modularity aims to reduce manufacturing time by performing different activities simultaneously and providing modules with the help of specialized suppliers, which theoretically contributes to technological improvements. Figure 5.1 illustrates one example of design modularity application, comparing modular architecture with an integral architecture of a vehicle.

Figure 5.1 – Inferior structure of a general vehicle – integral: left-hand side and modular: right-hand side.



Source: Paralikas et al. (2011)

5.3 RESEARCH METHODS

This study developed a preliminary literature analysis about the benefits and difficulties of adopting modularity in design within the context of the automotive industry. It is a theoretical-conceptual study as established in the literature (FILIPPINI, 1997; BERTO; NAKANO, 2000). To reach the study's objective, publications of interest were retrieved through a search in the following databases: Scopus, ISI Web of Knowledge, Emerald, SciELO, Science Direct. Some articles published in the International Journal of Automotive Technology and Management, which has restricted access and they are not available at CAPES journals portal (Coordenação de Aperfeiçoamento de Pessoal de Nível Superior – a Brazilian government agency for research support). It is important to mention that some articles had no free access and, therefore, they were not considered in the paper portfolio. This is one of the study limitations. To assist in recording and organizing the articles, the EndNote® X5 software was used. The following key expressions were used to search the databases: "modularity", "modularization" (and its variation, e.g. "modularisation"), "modular", "modular design", "modular product" in combination with the terms "automotive industry" and "auto industry".

The period between 2007 and 2012 was considered, since one of the objectives is a literature update on the subject verifying recent trends and characteristics of the related practices of design modularity, focused in the automotive industry. To organize the article portfolio, papers were classified into two groups: "conceptual research" and "empirical research". Conceptual studies were sub-classified into "theoretical-conceptual", "literature review", "simulation" or "theoretical modeling".

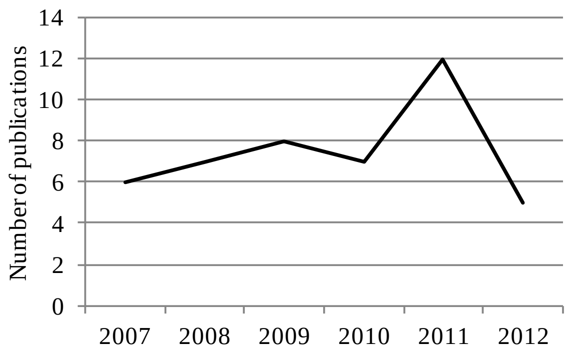
Empirical investigations were stated as "survey", "case studies" - single or multiple according to Yin (2005), "action research" or "experiment".

The nature of the data was also analyzed ("qualitative" or "quantitative"). The modularity typology focused on modularity in design/product. Production/process modularity and modularity in use will be investigated and analyzed in the future. Finally, data were also recorded in a Microsoft Excel® spreadsheet in order to build graphs and tables. Essentially, all paper contents (methods, theory or empirical results, and conclusions) of the papers were analyzed. The more related benefits and difficulties adopting design modularity in the automotive industry were identified, from both perspectives (automakers and suppliers). Finally, an analysis of all features found in the papers was conducted and presented next.

5.4 RESULTS AND DISCUSSION

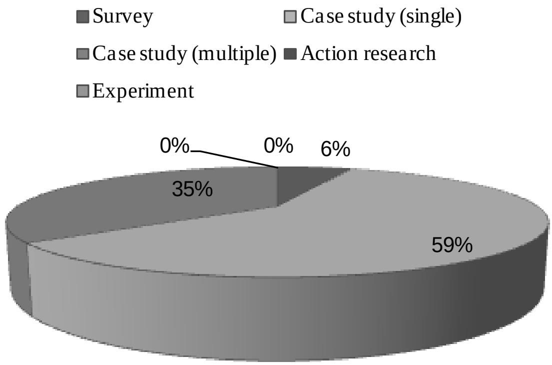
One hundred and twenty-three articles were retrieved, of which 45 were considered after a content analysis. For example, articles addressing modularity in software, electrical equipment or in an organizational perspective were discarded because they are out of the research scope. The article portfolio encompassed papers that developed design modularity in functional or physical perspective (in this specific case, in automotive vehicles). Figure 4.2 illustrates the number of papers published by year. As can be seen, the highest amount of publications (27%) occurred in 2011.

Figure 5.2 – Publications per year of design modularity in the automotive industry



Most articles employed have a qualitative approach (93%) and are empirical (76%), i.e. have empirical applications in order to investigate how design modularity principles are used. Empirical studies are distributed as shown in Figure 5.3. As can be seen in the figure, most articles adopted it is highlighted case-based research as the methodological approach. The reasons for that were not identified.

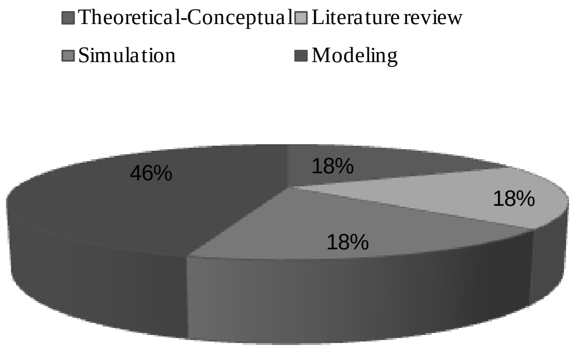
Figure 5.3 – Empirical articles distribution according to their research methods



A small portion of the article portfolio considered is theoretical papers (24%). Within this group, there are more theoretical modeling studies (see Figure 5.4). Modularity was a new subject in the early 2000's, as reported by Salerno et al. (2009). After that, conceptual works were more prominent as reported by Carnevalli et al. (2011) and Carnevalli and Cauchick Miguel (2009).

The 45 papers were published in 26 different journals, showing a wide range of periodicals publishing in this subject. The most prominent journals were: International Journal of Operations & Production Management (4 papers), Produção (3 papers) and IEEE Transactions on Engineering Management (3 papers).

Figure 5.4 – Conceptual articles distribution according to their research method



It was noted that the majority of Western countries publications focuses on production modularity instead of design modularity and the reverse occurs in the East countries, corroborating Carnevalli et al. (2011). After analyzing all papers, most cited benefits, difficulties, and recommendations when adopting modularity in design were identified. These findings are presented in the following sections.

5.4.1 Benefits of design modularity in the auto industry

Firstly, the identified benefits for automakers are:

- Reduction of product specifications and tasks complexity (POLITZE et al., 2012; CHRISTENSEN, 2011; BONJOUR; MICAELLI, 2010; CAUCHICK MIGUEL et al., 2009) through the partition of them along developed product components (modules). This simplifies and facilitates the comprehension about product specifications;
- Higher customization possibility, flexibility, variety and adjusting product and components use according to consumer needs and/or desires (CARVALHO et al., 2012; PARALIKAS et al., 2011; RAY; RAY, 2011; CHRISTENSEN 2011; CAUCHICK MIGUEL; HSUAN, 2010, WANG; KIMBLE, 2010; PANDREMENOS et al., 2009; CAUCHICK MIGUEL et al., 2009; KISTMANN; CARDOSO, 2008; MORAES; MACHADO, 2008; ORSATO; WELLS, 2007; JACOBS et al.,

2007). The authors state that modularity enables to increase customization and provides greater product variety to consumers and customers;

- Reduction in product development time (ZIRPOLI; BECKER, 2011a; 2011b; CARNEVALLI et al., 2011; OH; RHEE, 2010; CARNEVALLI; CAUCHICK MIGUEL, 2009; JACOBS et al., 2007). Although studies do not quantify how much is time reduction, the literature reports successful cases and suggests that adopting design modularity enables a faster development, since the manufacturing of components can be done simultaneously;
- Product development costs and resources reduction and quality increase (ZIRPOLI; BECKER, 2011b; RAY; RAY, 2011; MAHMOUD-JOUINI; LENFLE, 2010; OH; RHEE, 2010; SANTOS; FORCELLINI, 2009; JACOBS et al., 2007; DORAN et al., 2007). However, Carnevalli et al. (2011) report that the required resources to develop the project have not lead necessarily to a large costs reduction because these costs are included in the values charged by the suppliers responsible for each module. Because this is a tangible benefit, there is an opportunity to quantify this reduction through quantitative economic models, for example.

The following benefits were identified for suppliers:

- Suppliers become more specialized in manufacturing components and parts (ZIRPOLI; BECKER, 2011b; MONDRAGON et al., 2009): with the modules division, suppliers have the opportunity of specializing in components that they are responsible. In fact, automotive industry suppliers are becoming specialists (MONDRAGON et al., 2009). Besides facilitating the division of labor, this can enable innovation and competitive advantage not only to suppliers but also to automakers, i.e. there is a mutual benefit;
- There are more independent and influent suppliers in the product development, since its conception (RODRIGUES et al., 2012; ZIRPOLI; BECKER, 2011a; 2011b; CERRA et al., 2011; SALERNO et al., 2009; RODRIGUES et al., 2009; SACOMANO NETO; TRUZZI, 2009; MELLO; MARX, 2007a; 2007b; ORSATO; WELLS, 2007). In addition, there is higher participation in modular design (RODRIGUES et al.,

2012; PRIETO; CAUCHICK MIGUEL, 2011; CERRA et al., 2011). When partitioning the product in different modules, suppliers have an increased degree of autonomy in developing products. It is important to point out that, in general, automakers still have control of all design specifications;
- Suppliers in a modular maturity degree have more potential in adding value to automakers and their business through constant competitive advantages generation, contribution and commitment to product "customization" (PRIETO; CAUCHICK MIGUEL, 2011). This can also enable long-term contracts and improve and strengthening the relationship between OEMs (Original Equipment Manufacturers) and suppliers. In addition, there is a possibility of higher information sharing and learning with the automaker (ZIRPOLI; BECKER, 2011b).

5.4.2 Difficulties in adopting design modularity

The main difficulties adopting design modularity in the automotive industry were also raised. To automakers the difficulties are:

- Excessive component outsourcing (ZIRPOLI; BECKER, 2011a; 2011b). Transferring responsibilities to suppliers brought issues in developing new products since there was a control loss on product specifications by OEMs (ZIRPOLI; BECKER, 2011a; 2011b). Corroborating this argument, Carnevalli et al. (2011) reported module knowledge migration to suppliers, i.e. they began to take over key decisions in new product development because they became the main responsible for modules;
- Increased dependence on suppliers (RODRIGUES et al., 2012; ZIRPOLI; BECKER, 2011b; CARNEVALLI et al., 2011), which can cause difficulties in productive and organizational processes according to the relationship between automaker and suppliers. Furthermore, many defined specifications during pre-product development will only be observed and tested after components assembly, which can generate high costs (even recalls depending on the issue) in the case of non-compliance and/or inconsistency in full assembled product. (ZIRPOLI; BECKER, 2011b);

- OEMs engineers might stagnate or even lose their knowledge during the components development, as suppliers become experts and deepen to generate improvements in them (RODRIGUES et al., 2012; ZIRPOLI; BECKER, 2011a; 2011b; PANDREMENOS et al., 2009). In a case study in a European automaker, ZIRPOLI; BECKER (2011a) reported that the company had lost the competence of designing some product components (panels, suspension, and safety system). This is an example that demonstrates such difficulty;
- Product modularity is not suitable to solve performance issues in the product (ZIRPOLI; BECKER, 2011a; 2011b). The fact that the product is developed by modules contributes for the responsibility division in components assembly. However, ensuring effective assembly does not imply necessarily that the product as a whole will have the same effectiveness (ZIRPOLI; BECKER, 2011b). This occurs because modules integration influences one another. Thus, it emphasizes the need to identify the product performance tradeoffs, as reported in literature (e.g. ZIRPOLI; BECKER, 2011a);
- Complete vehicle redesign is necessary to fully explore modularity benefits, which takes time and additional product development costs (PANDREMENOS et al., 2009). An example of this difficulty is reported in Rodrigues et al. (2009), where a new truck needed a completely new cabin, engine, and suspension to enable the project.

The following difficulties were identified for suppliers:

- Larger needs and efforts to adequate their (productive and organizational) processes to adaptation towards design modularity (CARNEVALLI et al., 2011). In general, automakers have more adequacy conditions to modularity actions, being suppliers the ones that need more efforts to adapt;
- Suppliers may also have a dependency relationship with automakers as they can have full control of projects (CERRA et al., 2011; MELLO; MARX, 2007a; 2007b) and define the involvement degree of suppliers in design (SALERNO et al., 2009). This can cause restrictions and limitations to suppliers during modules development, which can difficult search for innovation in components - from suppliers;

– Excessive autonomy due to specialization can bring difficulties in the relationship with the OEM since it does not have much interest in implementing technologies which they do not fully understand (MONDRAGON et al., 2009). Again, suppliers have limitations about to propose and develop innovations beyond incremental if automakers do not understand clearly ideas offered by suppliers.

5.4.3 Literature recommendations regarding design modularity adoption

From the literature analysis, it was possible to observe some recommendations in the literature with regard to the adoption of design modularity in the automotive industry. Modular products manufacturers may develop ways to strengthen communications among modules development teams (LAU et al., 2011; PAN et al., 2007). Thus, the responsibility and transfer definition are improved as well as the relationship between OEMs and suppliers. Furthermore, it is necessary to define design activities clearly to separate which will be automaker and supplier responsibility (ZIRPOLI; BECKER, 2011b). Moreover, due to increased product flexibility, additional efforts are needed to coordinate and manage modular components development (MIKKOLA, 2007). Another important feature in the product development concerns suppliers' participation intensity. In locally conducted new product development projects, it was observed most influent suppliers during vehicle development in comparison to cars developed at the headquarters located abroad (SALERNO et al., 2009).

The connection between the division of labor ("who does what?") and knowledge ("who knows what?") cannot simply be managed based on modular product architecture (BRUSONI, 2005), i.e. it is a more complex activity. In addition, the management of each system individually does not imply that an effective vehicle integrated management will occur (ZIRPOLI; BECKER, 2011a). Regarding production systems aimed at enabling design modularity, they need to have the flexibility to produce all variants required quickly (PARALIKAS et al., 2011). Aiming at achieving a higher customers satisfaction at a lower cost and to do it effectively, it is necessary a good tolerance management in place (PANDREMENOS et al., 2009) to provide standardized components and avoid excessive clearances and interferences, assembly inconsistency, etc., during product variants production. Regarding the impacts of design modularity in the supply chain, as in Lau et al. (2007), it was not possible to find consensus in the literature about those effects.

Finally, it is important to seek innovation in modules that have higher perceived value according to customers and reuse modules that do not add value to the product (ROBERTSON; ULRICH, 1998). This can generate competitive advantage to OEMs and suppliers because organizations will be strategically focused on their customers. Additionally, considering an operational viewpoint, reusing modules would minimize operational costs of manufactured components. However, it is important to point out that supply innovative proposals need to be understood by automakers. Otherwise, the actions might not become viable and attractive precisely for this reason (MONDRAGON et al., 2009). Having presented the results, the next section presents the conclusions of this study.

5.5 CONCLUDING REMARKS OF THIS CHAPTER

This chapter aimed to conduct a preliminary literature analysis on design modularity in the automotive industry. Although this is the first part of an ongoing study, it was possible to identify a number of benefits and difficulties recently reported in the literature. Firstly, in the design point of view, modularity brings contributions mainly regarding the possibility of fulfill market needs and expectations in a more agile and flexible manner. Moreover, modular product conception is facilitated through component sharing, simplifying the product and turning it less complex. This implies in contributions to product architecture knowledge.

Concerning research methodology in the publications, empirical investigations have gained more attention than conceptual studies. This means that the most recent interest is to investigate how modularity has been adopted within the industry context by conducting empirical studies. Nevertheless, single case studies are prominent, despite their limitation due to their external validity. Positively, multiple case studies are also present in the publications. With regard to conceptual papers, most interest is to establish a framework for future empirical investigations.

In the automotive sector, benefits have been more exposed than difficulties. It is reported that OEMs have more benefits than suppliers since the latter have more difficulties to adapt their organizational and productive processes towards design modularity. In general, automakers have benefits in product architecture and development, increasing flexibility and variety offering to customers, more intense relationship with suppliers (which also have benefits in this sense), and product development time and costs reduction (although there is no quantification in the literature of how much time is reduced). Suppliers can specialize and may contribute with modules innovation, establish long-term contracts with OEMs, have more autonomy in components development as well as and higher influence in developing product architecture since their pre-conception.

OEMs main difficulties concern loss of control regarding product specifications, which turns to be suppliers responsibility, bringing consequently larger suppliers dependence and more coordination demands to manage manufacturing activities. Suppliers have issues about increased responsibility in product development and innovation restrictions during the product development process since automakers have control of most activities.

Recommendations for design modularity adoption in the auto industry involve aspects such as clearly define design and product activities, methods and tools to increase communication among teams (OEM and suppliers), seek innovation in the most relevant (according to customers) modules, and organize the production system to generate the variants needed.

It is expected that this study brings theoretical contributions with regard to benefits, difficulties and recommendations observed in literature when adopting design modularity in the automotive sector. Future research involves developing a broader theoretical framework, considering the main influent aspects on vehicle development as well as to analyze empirically implications about the recommended actions in OEMs that adopt modularity. In addition, it is intended to enlarge the study to a more robust theoretical context, by considering papers on modularity in production and modularity in use in the automotive industry as well as the relationships among the various typologies of modularity. Additionally, this chapter shows that MID is the most explored approach, but MIP also emerges as a significant explored modularity approach. In this sense, the next chapter presents the beginning of the conceptual framework building, through a literature critical analysis on MID and MIP, their concepts and possible relationships in the automotive industry.

6 RELATIONSHIPS BETWEEN MODULARITY IN DESIGN AND PRODUCTION IN THE AUTOMOTIVE INDUSTRY: TOWARDS A THEORETICAL FRAMEWORK DEVELOPMENT

This chapter presents the contents published in the fourth article[16] of this thesis. It focuses on the relationships between modularity in design (MID) and production (MIP). After analyzing 60 papers on MID and MIP in automotive companies, it was observed that some publications suggest that relationships between MID and MIP can be two-ways, i.e. not only the former affects the latter, but the latter also affects the former. Additionally, it presents a scenario of the Brazilian automotive industry as a reference to modularity application and an auspicious context for further empirical investigation. Conclusively, the relationships between MID and MIP are relevant and future studies should emphasize how they produce managerial benefits and/or drawbacks.

6.1 MODULARITY IN DESIGN AND MODULARITY IN PRODUCTION IN THE AUTOMOTIVE INDUSTRY

The automotive industry is one of the most complex industries in terms of technology and agents involved in the innovation process. In order to reduce this complexity, modularity concept has been widely used in the automotive sector. This concept was originated in the computer industry during the 1960s, generating competitive advantage and demonstrating significant importance in product development process (ARNHEITER; HARREN, 2006).

Within this context, a relevant issue was raised, which is the relationships between modularity in design (MID) and modularity in production (MIP) in the context of the automotive industry. MID and MIP relationships have recently begun to attract scholars’ attention, as many European, Japanese and North-American automotive firms are applying this concept to analyze how product and production modularity affect efficiency and competitiveness. Additionally, emerging economies like Brazil has been conducting more added-value product development activities in the past decades, which lead to some important changes

[16] KUBOTA, F.I.; CAUCHICK MIGUEL, P.A.; HSUAN, J. Analysis of the theoretical relationships between product and production modularity and their implications in the automotive industry. Proceedings of the 22nd EurOMA Conference, Neuchâtel, Switzerland. 2015.

within the automotive sector (SALERNO et al., 2009), particularly from the modularity perspective.

Nevertheless, research about how MID might be connected to MIP (or vice-versa) is still scarce, even though some research have been pointing out the importance of this topic (e.g. JACOBS et al., 2011; CAMPAGNOLO; CAMUFFO, 2010). For instance, Brusoni and Prencipe (2001) argue that modularity in production and processes sometimes seems to be an inevitable result of the higher degree of product modularity. On the other hand, Rodrigues et al. (2012) state in their study that modularity concept can be deployed in production without the product being necessarily designed in modules. Campagnolo and Camuffo (2009) state that it is not clear whether product modularity determines outsourcing or outsourcing activities and tasks affect product modularity.

From this scenario, the following research questions emerged: ‘Does modularity in design leads to modularity in production (or vice-versa)?’ ‘Do such cause and effect relationship (if happens) bring practical benefits and/or drawbacks to automotive companies?’ Finally, ‘What are the specific drivers and/or concepts behind these relationships and how can they enhance modularity’s managerial benefits or generate drawbacks in the automotive companies?’

This study analyses the possible relationships between modularity in design (MID) and modularity in production (MIP) theoretically. Moreover, it intends to verify if these cause and effect relationships bring managerial and strategic benefits as well as challenges for companies that adopt them. The argument developed in this paper culminates in a conceptualization of modularity that considers an integration and existence of causal relationships between MID and MIP. In addition, this paper details how these relationships occur, through specific conceptual elements that lead these MID and MIP connections.

The remainder of the paper is structured as follows. Section 2 describes the research methods used to conduct this study. Section 3 shows the findings from this study. The paper finishes with a discussion of contributions in section 4, followed by conclusions, limitations, and further research opportunities (section 5).

6.2 RESEARCH METHODS

The bibliographic search involved publications in peer-reviewed journals focused on the relationships between MID and MIP in databases such as Scopus, ISI Web of Science, Engineering Village (Compendex), Wiley Online Library, Blackwell, Emerald, and Springer. The initial search, using the terms ‘modularity’, ‘modular’, ‘modularization’, ’modularisation’ and ‘automotive’, yielded 307 papers. The search was refined after eliminating all papers that did not focus on modularity in design and modularity in production since the interest is the relationships between these modularity typologies. The final selection included 60 references from the engineering and management literature, mostly within the context of the automotive industry. These papers focus most on the impact of MID and MIP in aspects such as company’s performance, performance integration, supply chain integration, managing complex products, etc. Few papers focus specifically on the relationships between MID and MIP, which suggests an unexplored field of research.

Through a hypothetical-deductive method, based on Nunes and Bennett (2008), the focus was on building new conceptual evidence regarding the conceptual elements found in the literature on modularity and, through these concepts, establishing theoretical relationships between product and production modularity. Then, a theoretical framework is proposed regarding this relationship. Moreover, only MID and MIP was considered because these two approaches are the most exposed in literature, also mostly observed in the automotive industry in terms of practice and maturity degree. Conceptual elements of modularity were taken into consideration, since these concepts may be important to analyze the relationships between modularity typologies and to verify the feasibility of cause and effects relationships. Finally, it was investigated in what circumstances and how MID and MIP are linked and the possible implications in technical and organizational perspectives.

The choice for the automotive industry is due to its intense competition. Furthermore, modularity concept is relatively new in the automotive sector, introduced in the early 1990s. In this sense, there are still many challenges to overcome about modularity in the auto industry (RO et al., 2007). Sanchez (2013) suggests that in spite of the effective strategic use of modularity by a few automotive firms, in the automotive industry generally there is still comparatively limited understanding of what modular strategies really mean and of the organizational changes necessary to implement modularity strategies effectively. Little is known about the implications of product architecture on organizational design both inside the company and the entire supply chain in the context of changes towards a more modular product architecture (RO et al., 2007). In the next section, the findings of this study are presented. In addition, the analysis was narrowed down to give focus in the Brazilian automotive industry since it is one of the largest emerging markets in the world, responding in part to a call for more research on this region (HOSKISSON et al., 2000). Besides, Brazil has the largest range of automobile brands being produced in a single country (PARENTE et al., 2011).

6.3 FINDINGS

This section presents the specific conceptual elements involved in these relationships and a summary of the Brazilian automotive case regarding MID and MIP.

6.3.1 Conceptual elements involved in the relationships between MID and MIP

The first evidence found on causal relationships between MID and MIP is when MID leads to MIP. For example, Sanchez and Mahoney (1996) argue that modular product architecture can work as a 'leverage' for engineering outsourcing. However, the same authors, as Sako (2003) mentions, recognize that these relationships can be in both ways (this two-way trajectory will be discussed later). In another argument in this direction (MID to MIP), Brusoni and Prencipe (2001) affirm that modularity in production sometimes seems to be an inevitable result of higher product modularity degree.

Underpinning this causal relationship trajectory, Paralikas et al. (2011) say that product structure influences its production since companies need to organize their production processes in an agile manner in order to provide all product variants developed. In addition, modular products can facilitate organizational redesign by companies (HOETKER, 2006), one of the influent aspects in modularity in production. Nevertheless, other authors argue that MIP might lead or affect MID since in some cases manufacturing structure need to be taken into account before designing modular architecture. In this perspective, a certain type of product architecture is restricted by the organizational capabilities of each company (RO et al., 2007), i.e. it is necessary to evaluate all productive processes conditions and structure before establishing a redesign of a new modular product architecture. Changes in the hierarchies in production systems and/or inter-firm systems cause tension in their relationships with product architecture, and thus encourage the redefinition of product architecture (TAKEISHI; FUJIMOTO, 2003).

Although some authors argue that the relationship can be either from MID to MIP or vice versa, the literature shows more evidence demonstrating that relationships between MID and MIP can actually be a two-way trajectory, considering that both trajectories might occur. Takeishi and Fujimoto (2003) argue that the relationship between product architectures and inter-firm systems is two-way – not only the former influences the latter, but also the latter has some impact on the former. In addition, the trajectories of causal relationships between modularity typologies depend on the unit of analysis considered (FIXSON; PARK, 2008). Corroborating with this, Frigant and Talbot (2005) say that differences in the trajectories of adopting modularity are the result of (i) previous and the current configuration of the industry in question; (ii) different product characteristics; and (iii) rate of technological change and organizational learning.

The following conceptual elements that influence on degrees of modularity in design and production can be identified: outsourcing, standardization, commonality, functionality, product variety, interdependence between modules, co-design, and product platform development. Through the definitions of the conceptual elements, it is established here how MID and MIP are related to each other. Table 6.1 presents the most used and cited conceptual elements in the literature, followed by a brief description and the modularity typologies, which they are commonly related.

Table 6.1 – Modularity's conceptual elements

Conceptual element	Description	References
Outsourcing	Consists of transferring assembly and/or engineering activities to suppliers. The level of outsourced modules/ components, as well as the level of influence suppliers have on the product development process, affect connections between MID and MIP.	Brusoni e Prencipe (2011); Ro et al. (2007); Mikkola (2003); Collins et al. (1997).
Standardization	Makes it possible to recombine the components of products without an elaborate adaptation of interfaces.	Jacobs et al. (2007); Brusoni and Prencipe (2001); Baldwin and Clark (1997).
Commonality	Refers to the level of modules/components that are common to different products. Sharing common parts contributes to MID and MIP relationships.	Pasche and Sköld (2012); Fixson (2007); Fisher et al. (1999).
Functionality	Refers to the ability or capacity of performing a task or function. Modules/components of a product may perform one or more functionalities according to the product design.	Sushandoyo and Magnusson (2012); Mikkola (2006); Baldwin and Clark (2000).
Product variety	Consists of offering a variety of products that the company makes available in the market. The bigger the variety, the higher is the possibility of offering product diversity.	Zeppini and Van der Bergh (2013); Liu et al. (2010); Pil and Holweg (2004).
Interdependence between modules	Refers to the degree of structural independence the modules/components have among themselves. The more independence they have, the more coupling and uncoupling autonomy and capacity the modules have, still being able to work together as a whole.	Zirpoli and Becker (2011); Baldwin e Clark (2000).
Co-design / Co-development with suppliers	Refers to the degree of suppliers' involvement in product development. Suppliers involved in earlier phases of the product development process tend to be more influent in the product architecture definitions.	Zirpoli and Becker (2011); Salerno et al. (2009); Campagnolo and Camuffo (2009); Ro et al. (2007).
Product platform	Consists of a central strategy for companies to handle agile manufacturing and new product development, which incorporate several approaches. Also can be a strategy to manage costs and variety in R&D and production.	Pasche and Sköld (2012); Hsuan and Hansen (2007); Sköld and Karlsson (2007).

Regarding outsourcing, Sako (2003) states that it can be made by (i) designing modules and produce them in-house first, before outsourcing; (ii) outsourcing non-modular components before moving towards modular design; or (iii) simultaneously implementing modular design and outsourcing. Through these possibilities, one can observe that path 1 suggest modular design before considering modular production (through outsourcing modules and then more suppliers involvement) while path 2 suggest outsourcing before structuring product in modules. Lastly, path 3 seems to have the higher relationships between MID and MIP, since deals both with modular design together with outsourcing. In this context, Campagnolo and Camuffo (2009) argue that still it is not well defined if MID leads to outsourcing or if outsourcing of activities and components leads to product modularity. Apparently, both ways might occur, but it depends on each context and project developed.

Although it might be beneficial for OEMs and suppliers, some tradeoffs might occur when outsourcing. Zirpoli and Becker (2011b) studied companies that faced problems in conducting outsourcing engineering tasks and activities, especially when trying to obtain higher product performance since modular product design as an ex-ante integration mechanism is not always effective for the integration of performances. Loss of learning by doing beyond the degree required to maintain component-specific knowledge represents a limit to design and engineering outsourcing (ZIRPOLI; BECKER, 2011b).

The application of the standardization concept is established in the product development early stages, design specifications and the respective tolerances for each module. Thus, connections between product and production modularity through standardization occur minimizing variability in manufacturing processes, a key aspect of lean manufacturing that can be facilitated anticipating the inherent commonality of modular product architecture (JACOBS et al., 2007). Furthermore, MIP needs standardization in order to favor process redesign and/or agile inclusion of new modules to meet product requirement changes (MIKKOLA, 2006).

The commonality is a concept more usual when studying products than processes, and explores the idea of using identical components in a one-per-product setting, but in different products (FIXSON, 2007). This concept is characterized by grouping similar module variants to generate similar variations of a specific module type (JIAO et al., 2007; WATANABE; ANE, 2004). In this sense, specifications must be visibly defined to avoid inconsistencies connecting product modules and components. This suggests that commonality has also a strong connection with standardization of product interfaces, modules, and components. However, in terms of product variety, commonality might bring some issues. For instance, Pasche and Sköld (2012) argue that the products become very similar with higher degrees of commonality among different products and/or brands.

Functionality is used to define how modules will be composed according to vehicle architecture and the functions of each module and subsystems that compose the vehicle as a whole. From this point, it is possible to build physically modular arrangement and their connections within the "systems" (see more in RO et al., 2007), since modules and their couplings are organized towards manufacturing and assembly processes, considering limitations and potentials of the current productive arrangement. Manufacturing processes limitations are relevant because according to the product architecture, there might be the risk of the project to require high investment changes in the supply chain, which can inhibit the desired product conception.

Regarding product variety, Sanchez (2013) argues that the ready configurability of new product variations within a modular architecture substantially improves an organization's ability to offer greater product variety. Modular architectures enable the creation of families of products in one development effort, not just single product designs. Product variety is a concept related to customization level and it is usually defined during the design phase in order to specify which components/parts will be able to customize and strategically selected according to customers' expectations (STONE et al., 2000). Through modular product architecture, it is possible to achieve products variants at low cost (STONE et al., 2000). Thus, seems that product variety is developed in the strategic objectives through modularity, prior to modular design activities, to then arrange it inside the manufacturing processes.

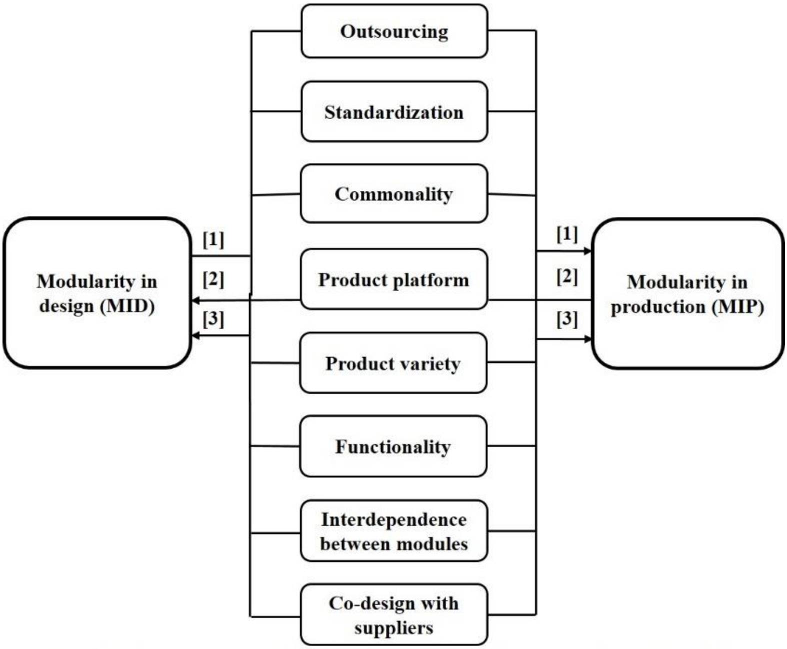
Interdependence between modules is a concept that is influenced by other conceptual elements, especially standardization and functionality. Modules interact only between standardized interfaces (BALDWIN; CLARK, 2000; ZIRPOLI; BECKER, 2011b), because inconsistencies in this situation undermine coupling and connection between product modules, preventing its building as a whole. It is undertaken here that interdependencies between modules need to be developed during product development early phases and then transferred to the production line, suggesting a MID to MIP direction.

Regarding the suppliers' involvement in design (co-design), Jacobs et al. (2007) defend that product modularity has direct and indirect effects on cost, and indirect effects are the result of higher suppliers' integration and design and manufacturing product integration. In this sense, one can affirm that suppliers' involvement in vehicle design with the OEMs enhances modularity both in design and in production since suppliers will not only participate in the assembly process, but also in the early stages of product development processes.

The last concept found, product platform, is established during product development process, in order to obtain greater modularity benefits such as product variety at low costs, sharing commonalities in modules/components along various vehicle models and brands, lead-time reduction and a more agile response to market demands. Product platform usually is defined during the product development process, i.e. prior to developing the production process to build all vehicle variants from the planned product platform.

However, when companies change their product platform structure, significant investments in the production processes are needed. Mercedes Benz (2014) example (cited in section 3.1) is one of the evidence that corroborates this relationship between MID and MIP through product platform development. Finally, Figure 6.1 shows a proposed framework with the identified conceptual elements involved in the relationships between MID and MIP and the possible trajectories of these causal relationships.

Figure 6.1 – Conceptual elements involved in the relationships between MID and MIP



[1] Modularity in design (MID) leading to Modularity in production (MIP); [2] Modularity in production (MIP) leading to Modularity in design (MID); [3] Two-way relationships between MID and MID

6.3.2 MID and MIP: The Brazilian automotive scenario

Since the automotive industry introduction in Brazil, significant changes in relationships between companies working in this supply chain took place, especially regarding the location and positioning of product development activities and organization of production processes (SALERNO et al., 2009). With the arrival of new manufacturers, Brazil returned to a prominent and important position globally, mainly for small and medium vehicle manufacturers in the Latin American market (TOLEDO et al., 2003). In addition, new products were introduced in the local markets, expanding shopping alternatives for consumers and driving companies already established in Brazil to conduct improvements in their manufacturing processes and product development activities, aiming competitive prices, better quality and innovation (TOLEDO et al., 2003).

The automotive industry around the world has also joined the ‘movement to modularity’, and in recent years, a number of firms have implemented various approaches to modular design and production (SANCHEZ, 2013). The same happened with Brazilian companies, where the most classical case is the renowned modular consortium in Resende (RAMALHO; SANTANA, 2002), which has a strong supplier integration with the automaker within the plant. Therefore, modularity’s conceptual element ‘co-design with suppliers’ is strongly applied in this case. Ramalho and Santana (2002) state that the unique feature of the plant’s production system rests on the relationship between the assembler (VW) and its component suppliers. These were involved in a joint enterprise to establish a ‘modular system’ of production. In this system, the component suppliers finance a part of the factory and organize the assembly of their components on site. As such, the assembler has the main role of coordinating production and marketing the vehicle.

6.4 DISCUSSIONS

One of the difficulties found in this study is the variety of “modules” definitions used in the automotive industry as well as in other industries. This conceptualization’s lack of alignment, along with a vague understanding of modularity concept, might bring issues especially during empirical studies and practical adoption of modularity within companies. Therefore, it may be pointed out the importance of establishing clear conceptual definitions of “modules” and “systems”, avoiding inconsistencies on studies regarding modularity, especially when conducting empirical research on companies.

This study enables to observe that there are, in high or low extent, clear connections between MID and MIP. Although some studies argue that it is possible to structure some modularity typology without necessarily influencing another, most publications consider that structuring modular product architecture brings technical and organizational impacts to production modularity and vice-versa. In this sense, evidence suggests that usually product modularity is prioritized and later modularity concepts are used in production, simplifying manufacturing processes. This occurs especially with new products when designers and engineers have more autonomy to build product and/or platform architecture. Additionally, it is noticed that relationships between MID and MIP can be stronger if managers and engineers involved have a mature knowledge about modularity principles and concepts, considering not only technical aspects but also strategic and mid- and long-term goals.

6.5 CONCLUDING REMARKS OF THIS CHAPTER

This paper offers three main contributions: establishing in a systematized way the causal relationships trajectories between MID and MIP, analyze what are the specific conceptual elements involved in MID and MIP relationships and offering some propositions of how these cause and effect relationships can increase practical and/or managerial implications. Considering that relationships between MID and MIP vary according to each company's context, it is proposed that the trajectories on building MID and MIP depend on the focus of each OEM as well as the context where they are involved and the focus of each developed vehicle.

As theoretical contributions, the results show that it is not possible to establish only a one-way relationship between MID and MIP, considering that these relationships have conceptual elements that affect both product and organizational architecture. The importance of these relationships regards on observing what companies prioritize more (MID or MIP). From a theoretical perspective, literature is still not well developed concerning relationships and directions between MID and MIP. There is still more issues to be explained, and the conceptual elements involved in these relationships can be a way of demonstrating how MID and MIP are related.

Since this study is a theory-building effort, the further empirical study is needed. Some interesting insights about the practical implications of MID and MIP relationships might emerge through this next step. In addition, the continuity of this work intends to check if practices are aligned or conflicting to what literature already shows.

The following opportunities for further studies are suggested:

– Explore how MID and MIP are linked within the Brazilian automotive context, considering the platforms and vehicles most recently developed specifically in the context of local markets since Brazilian automotive context is still scarce regarding literature and research focused on MID and MIP relationships. In addition, Brazilian automotive industry is an interesting field regarding application of modularity concepts and studies in this context might bring relevant contributions to the MID and MIP relationships subject;

- Compare product and production modularity relationships in the Brazilian automotive industry, where the topic is considerably recent, to other developed markets, such as the European automotive industry, in order to analyze the main differences when applying modularity in such different contexts.

Despite the fact that those conceptual elements were identified and analyzed, there is a lack of clarity in terms of how each concept establish relationships between MID and MIP. In this sense, the next chapter presents the enhancement of the conceptual framework.

7 ANALYSIS OF MODULARITY IN DESIGN AND PRODUCTION RELATIONSHIPS: PROPOSAL OF A CONCEPTUAL FRAMEWORK

This chapter proposes a conceptual framework of MID and MIP relationships, illustrating the main conceptual elements involved in modular design and production. This chapter represents the contents of the fifth article[17][18] of this thesis. It presents the relationships between modularity in design (MID) and modularity in production (MIP) in the automotive industry, in terms of how automotive companies obtain benefits and/or drawbacks through MID/MIP relationships.

7.1 CONTEXT OF THE RELATIONSHIPS BETWEEN MODULARITY IN DESIGN AND MODULARITY IN PRODUCTION

Modularity has attracted the attention of numerous management scholars, especially in the product, production systems and organization (CAMPAGNOLO; CAMUFFO, 2010), due to its potential of generating competitive advantage and significant importance in product development process (ARNHEITER; HARREN, 2006). There are two distinct perspectives/dimensions on the use of modularity, which are modularity in design (MID) and modularity in production (MIP). The former aims at decomposing complex products into complete functional subsystem units, which can be designed and manufactured independently; this enables construction of different products by combining subsystems, reducing complexity simultaneously while integrating functionality (PERSSON, 2006; BALDWIN; CLARK, 1997). The latter is characterized by organizing production processes into standardized groups (JACOBS et al., 2011; HOOGEWEEGEN et al., 1999) that have little strong organizational ties (FINE et al., 2005), permitting resequencing and tooling with few losses in functionality due to each production module works as a fairly autonomous unit (SCHILLING; STEENSMA, 2001). It focuses on the organization of the manufacturing

[17] KUBOTA, F.I.; HSUAN, J.; CAUCHICK MIGUEL, P.A. Theoretical analysis of the relationships between modularity in design and production. **International Journal of Advanced Manufacturing Technology**, v. 89, n. 5-8, p. 1943-1958, 2017.
[18] The final publication is available at Springer via http://dx.doi.org/10.1007/s00170-016-9238-4.

processes in order to increase flexibility, reduce complexity and reduce lead-time and costs, by establishing more independent and autonomous processes, characterizing the whole manufacturing processes as modular (PERSSON, 2006; JACOBS et al., 2011; LUCARELLI et al., 2015).

Within this context, an important issue can be raised: the relationships between MID and MIP. Relationships between MID and MIP have recently begun to attract scholars' attention in terms of analyzing how product and production modularity affect efficiency and competitiveness. Extant research to date has conflicting views on the relationships between MID and MIP and pointing out the importance of this topic (e.g. JACOBS et al., 2011; CAMPAGNOLO; CAMUFFO, 2010; FIXSON, 2008; SCHILLING; STEENSMA, 2001). For instance, Brusoni and Prencipe (2001) argue that modularity in production and processes sometimes seems to be an inevitable result of a higher degree of product modularity. On the other hand, Rodrigues et al. (2012) state that the concept of modularity can be deployed in production without the product necessarily being designed in modules. Campagnolo and Camuffo (2009) state that it is not clear whether product modularity determines to outsource or whether outsourcing activities and tasks affect product modularity. Corroborating the relevance of this research, Jacobs et al. (2011) point out that the impact of modular product architecture in manufacturing processes emerges as an interesting opportunity for future research. Campagnolo and Camuffo (2010) say that it is important to take up the challenge of comprehensively analyzing how modularity may affect the simultaneous design of products, production systems, and organizations.

A handful of research papers have investigated how MID and MIP are organized, to what extent a relationship between MID and MIP can be established, and their benefits and drawbacks in the product development process as a whole. These relationships might be relevant since, through this analysis, it is possible to see how mature a company is when applying the modularity concept. Sanchez (2013) argues that some companies have a more advanced maturity level of modularity than others, mainly because the most mature companies go deep on understanding what modularity is and how it can be explored as part of the company's strategy, not only for technical design, reducing costs, and/or product variety. From this scenario, the following research questions emerged:

– *RQ1: Does modularity in design necessarily leads to modularity in production?*

- *RQ2: What are the specific drivers and/or concepts behind those relationships?*
- *RQ3: How can MID and MIP relationships enhance modularity's managerial benefits or generate drawbacks for companies?*

One of the industrial sectors that have been exploring modularity is the automotive industry. In recent years, many approaches to modular design and production have been implemented by a number of firms in this sector (SANCHEZ, 2013). It is one of the most competitive and complex industries in terms of technology and agents involved in the innovation process (HOLWEG, 2008). Passenger cars are the third most traded product and one of the most complex products (OEC, 2015). In order to improve managerial and technical practices to better deal with this complexity, the concept of modularity was adopted and since then it has been widely used in the automotive sector. In this sense, there are still many challenges to overcome about modularity in this industry (RO et al., 2007).

This paper aims to analyze the relationships between MID and MIP, in order to understand whether their cause and effect relationships bring managerial and strategic benefits (as well as challenges) to (automotive) companies that adopt them. The argument developed in this paper culminates in a conceptualization of modularity that considers an integration and existence of causal relationships between MID and MIP. Additionally, this paper details how these relationships may occur, through specific conceptual elements that produce these MID and MIP connections, as well as offers some propositions about the differences regarding benefits and difficulties according to each trajectory of these causal relationships.

In this context, this article aims to offer three main contributions. The first contribution is to establish the possibility of relationships between MID and MIP and the trajectories of these relationships. The second contribution is to present and analyze the specific conceptual elements involved in MID/MIP relationships since literature explaining the details of these relationships is limited to only a handful of papers. The third contribution is to offer propositions on how such cause and effect relationships can increase strategic, practical, and/or managerial implications based on four modularity drivers – marketing, production, financial, and technological (Sako, 2003). The intention is to analyze whether benefits such as increasing product quality, lead-time reduction, increasing innovation and more integration between product and organizational architecture can be obtained through MID and MIP relationships, as well as to examine the drawbacks that might happen when establishing causality between MID and MIP.

The remainder of the paper is structured as follows. Section 2 describes the research methods used to conduct this study. Section 3 shows the findings. Section 4 discusses the results. The paper ends with contributions, limitations, and further research opportunities.

7.2 RESEARCH DESIGN

In order to find publications regarding modularity, and especially peer-reviewed papers that explore relationships between modularity in design and production and/or relationships between product architecture and production structure, a literature search was conducted in the following databases: ISI Web of Science, Scopus, Engineering Village (Compendex), Wiley Online Library, Blackwell, Emerald, and Springer. The initial search, using the broad terms “modularity,” “modular,” “modularization”/“modularisation,” and “automotive,” yielded 307 papers. This search was refined after eliminating all papers that did not focus on MID and/or MIP since the main interest is the relationships between these two typologies. The decision of focusing only on MID and MIP is because these are the most common modularity approaches in the literature (JACOBS et al., 2011; CAUCHICK MIGUEL; HSUAN, 2010). The final selection included 61 references from engineering and management literature restricted to the automotive industry context.

The automotive industry was chosen because little is known about the implications of product architecture on organizational design, both inside the company and in the entire supply chain, in the context of changes towards more modular product architecture (RO et al., 2007). In addition, organizations need to change and learn constantly about their products and processes in order to attend market demands, and modularity is important in this scenario (WAGNER et al., 2015). Yet, it is important to understand the possible integration mechanisms that enhance more connections between modular product architecture and modular production (LIAO et al., 2013). Thus, more investigations about modularity are needed in this industry. In addition, Sanchez (2013) suggests that in spite of the effective strategic use of modularity by a few automotive firms, in the automotive industry generally there is still a comparatively limited understanding of what modular strategies really mean and of the organizational changes necessary to implement them effectively.

Those papers focused mostly on MID's and MIP's impact on aspects such as company performance, performance integration, supply chain integration, and management of complex products. Only a handful of papers focused specifically on the relationships between MID and MIP, which suggests an unexplored field of research. An analysis was conducted in the 61 retrieved papers to identify the main conceptual elements related to modularity. Then, a theoretical framework is proposed. The analysis was conducted through a preliminary inspectional reading (ADLER; VAN DOREN, 1972) focused on (i) finding the main concepts and definitions about modularity in the analyzed papers and; (ii) identifying the main concepts and elements that emerged in those definitions. After the inspectional reading, the analytical reading was conducted, following the logic of the content analysis proposed by Bardin (1977):

- Organization of the analysis: this first stage consisted of organizing the 61 papers related to MID and MIP in the automotive industry to support the final data interpretation. The study organized the analysis identifying modularity definitions, objectives, benefits, drawbacks and applications described in the papers. This step facilitated further data reduction and coding;
- Coding: all data regarding conceptual elements involved in the application of modularity and MID and MIP trajectories were extracted, transforming those sentences into a more precise data for classification by tracking the main concepts and the authors that support each evidence. Sentences regarding modularity were gathered in each paper and the concepts that emerged in those sentences were transformed into coded information such as "outsourcing", "co-design"/"co-development", "suppliers", "standardization", "commonality", etc. This step was important to identify and track the conceptual elements within the papers;
- Categorization: it consists of classifying documents and information from a data set for differentiation and regrouping. Semantics criterion is used to regroup the data. The concepts found and classified in the coding step were categorized into conceptual elements related to modularity. For instance,

"commonality" was found as a conceptual element. All papers regarding modularity involving commonality concept were analyzed to enhance information about the application of this conceptual element in modularity perspective. Then, information about MID and MIP relationships and conceptual elements were grouped and condensed into more simplified information for analysis;

– Inference: it refers to the analysis of causes induced from the effects. Thus, the following main results were gathered: MID and MIP possible trajectories; MID and MIP relationships conceptual elements and theoretical framework and some preliminary automotive examples of MID and MIP relationships.

Finally, modularity's conceptual elements (e.g. commonality, functionality, outsourcing, etc.) were extracted from the literature in order to establish how MID and MIP are connected as well as the trajectories of those relationships. Table 7.1 summarizes the steps conducted during literature analysis.

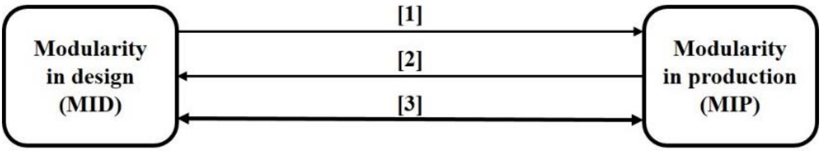
Table 7.1 – Steps of MID and MIP relationships literature analysis

Step	Description	Deliverable
1	Search for papers related to modularity in design and production	Portfolio of papers regarding MID and MIP
2	Search for papers restricted to the automotive industry	Portfolio of papers focused on MID and MIP in the automotive industry
3	Identification of modularity's definitions and the conceptual elements through inspectional reading	Conceptual elements involved in MID and MIP in the automotive industry
4	Analysis of how conceptual elements affect modularity decisions through content analysis and analytical reading	
5	Analysis of automotive examples found in literature and identification of the highlighted conceptual elements and relationships trajectories in each case	MID and MIP relationships in the automotive industry through modularity's conceptual elements
6	Establishment of MID and MIP relationships and trajectories through conceptual elements identified in the literature	

7.3 MODULARITY IN DESIGN (MID) AND MODULARITY IN PRODUCTION (MIP)

Steps 3, 4 and 5 from Table 7.1 are presented in this section. In the first trajectory (MID leading to MIP), the main arguments focus on how the conceptual elements act when modularity decisions during product design affect modularity in production procedures and adjustments in the plant. In the second case, concepts related to modularity in production that lead to changes in modularity in design choices are presented, which bring changes in product architecture features. Lastly, the conceptual elements that have a "two-way" role in MID and MIP relationships are highlighted, according to each context and situation that modularity decisions occur. As a result, Figure 7.1 illustrates the three possible trajectories between MID and MIP. The specific conceptual elements and the relationships trajectories are presented next.

Figure 7.1 – Possible relationship trajectories between MID and MIP



[1] Modularity in design (MID) leading to Modularity in production (MIP); [2] Modularity in production (MIP) leading to Modularity in design (MID); [3] Two-way relationships between MID and MID

7.3.1 Specific conceptual elements of the relationships between MID and MIP

Even though evidence in the literature shows causal relationships between MID and MIP, it is still not clear how they are related and what drivers or concepts foster these relationships. The majority of the literature states “it is possible” and “it is interesting” to have relationships between MID and MIP (e.g., JACOBS et al., 2011; CAMPAGNOLO; CAMUFFO, 2010). This study was designed to cast light on the questions about if relationships between modularity in design and in production necessarily bring benefits to automotive companies, what are the specific drivers and/or concepts involved in those relationships and; how can MID and MIP relationships increase benefits or drawbacks in automotive companies. The extant theory does not address whether modularity in products and processes are related to one another (JACOBS et al., 2011). In addition, empirical data detailing how these relationships take place with respect to the concepts and variables behind them are still scarce. Establishing the possible theoretical relationships prior to the empirical investigation is important because would be more precise to illustrate how the concepts are positioned according to each MID and MIP trajectory. Therefore, a search for specific conceptual elements that can establish and explain the MID and MIP relationships was conducted.

Accordingly, the identified conceptual elements were: outsourcing, standardization, commonality, functionality, product variety, interdependence between modules, co-design, and product platform development. It was observed that in design modularity, most of the impact of the decision different perspectives (project, organizational, costs, development time, etc.) at the product development process. In addition, the elements refer to standardization of components (SCHMICKL; KIESER, 2008), commonality (RO et al., 2007), functionality and interfaces (BALDWIN; CLARK, 2000). Whereas in modularity in production there is more concern in organizing the transferring of activities to suppliers and information sharing among the ones involved in the supply chain as a whole (DE WAARD; KRAMER, 2008) and standardizing production to turn processes more autonomous and independent (JACOBS et al., 2011). It is noteworthy that the conceptual elements discussed in this subsections are not exclusively interrelated to only one type of modularity, but do have a major relation to the related typology. In next section, each of the concepts is presented according to the relationship trajectory that they are more connected.

7.3.2 Relationships and trajectories between MID and MIP

7.3.2.1 When MID leads to MIP

The first evidence of causal relationships between MID and MIP is when MID leads to MIP. In this case, sometimes it seems that MIP is an inevitable result of the higher degree of product modularity (BRUSONI; PRENCIPE, 2001). This trajectory enables modular product architecture working as a “leverage” for engineering outsourcing (SANCHEZ; MAHONEY, 1996). Yet, product structure influences its production, since companies need to organize their production processes in an agile manner in order to provide all product variants developed (PARALIKAS et al., 2011). In addition, modular products can facilitate organizational redesign (HOETKER, 2006). As such, modular products call for modular organizations, and this correspondence is beneficial for enhancing organizational flexibility, eliminating the need for hierarchical coordination (SAKO, 2003).

In this relationship trajectory, some companies design product modules in-house first, before outsourcing (SAKO, 2003). Then, in this case, modular design defines modular production in terms of how the modules will be manufactured as well as what parts and modules suppliers will develop and build. Although outsourcing might be beneficial for OEMs and suppliers, tradeoffs might occur in some cases. Some companies faced problems in outsourcing engineering tasks and activities, especially when trying to obtain higher product performance since modular product design as an ex-ante integration mechanism is not always effective for performance integration (ZIRPOLI; BECKER, 2011b). Loss of learning by developing activities beyond the required to maintain component-specific knowledge represents a limit to design and engineering outsourcing (ZIRPOLI; BECKER, 2011b).

A platform is a large set of product components with standardized interfaces that are physically connected to a stable subset of a larger product and that can be shared among different final products (MAHMOUD-JOUINI; LENFLE, 2010). It is established during the product development process in order to obtain greater modularity benefits, such as product variety at low costs, sharing commonalities in modules/components along various vehicle models and brands, lead-time reduction, and a more agile response to market demands, i.e., prior to developing the production process to build all vehicle variants from the planned product platform. The major challenge of the platform design is to balance commonality and product differentiation: emphasizing the commonalities will reduce the design and production cost and delay as well while it will hamper the diversity of the products that will use this platform (HSUAN; HANSEN, 2007).

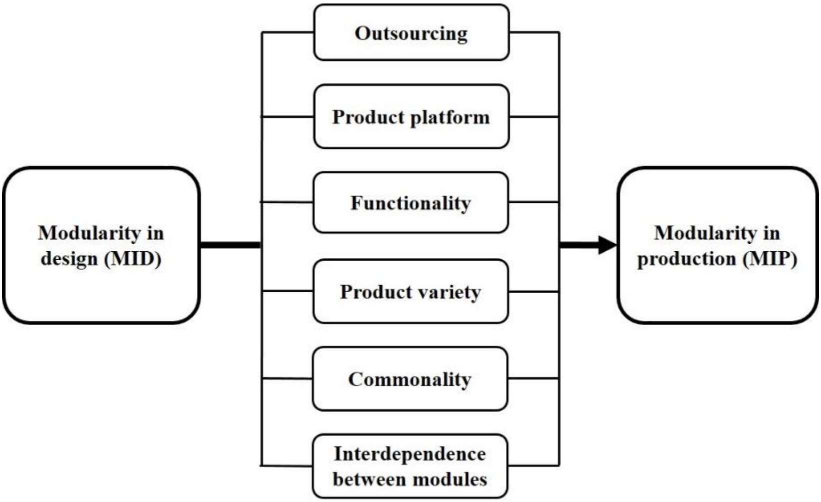
Functionality is used to define how modules will be composed according to vehicle architecture and the functions of the modules and subsystems that compose the vehicle as a whole. From this viewpoint, one can physically build modular arrangements and their connections within the “systems” (see more in RO et al., 2007), since modules and their couplings are organized towards manufacturing and assembly processes, considering limitations and potentials of the current productive arrangement. For example, in Renault’s Sandero vehicle conception, there is evidence of applying modularity mostly focused on functionality. The Sandero was divided into 30 different functions, which were associated with suppliers (panel, floor, suspensions, etc.), who participated in function development together with a Renault carmaker team (RENAULT, 2010).

Regarding product variety, the ready configurability of new product variations within a modular architecture substantially improves an organization’s ability to offer greater variety to the market (SANCHEZ, 2013). Modular architectures enable the creation of families of products in one development effort, not just single product designs. Product variety is a concept related to the customization level; it is usually defined during the design phase in order to specify which components/parts will be able to be customized and strategically selected according to customers’ expectations (STONE et al., 2000). Through a modular product architecture, it is possible to achieve product variants at lower costs (STONE et al., 2000). Product variety is a concept used in the platform dimension, especially in the automotive industry, creating flexibility in product architectures, where a product can be designed through versatile modules, common parts, common geometries, and standardized interfaces (WATANABE; ABE, 2004). Thereby, it seems that product variety is developed vis-à-vis strategic objectives through modularity, prior to modular design activities, and then afterward arranged into the manufacturing processes, in order to become more flexible and able to attend market variety demands.

Commonality, a concept found more in studies related to products than processes, explores the idea of using identical components in a one-per-product setting, but in different products (FIXSON, 2007). This concept is characterized by grouping similar module variants to generate similar variations of a specific module type (JIAO et al., 2007; WATANABE; ANE, 2004). In this sense, specifications must be visibly defined to avoid inconsistencies when coupling product modules and components. This suggests that commonality also has a strong connection with standardization of product interfaces, modules, and components. However, in terms of product variety, commonality might create other issues, because products become very similar, with higher degrees of commonality among different products and/or brands (PASCHE; SKÖLD, 2012). For instance, General Motors' Meriva vehicle is a practical application of the commonality concept found in the literature. This vehicle has parts and components borrowed from the Corsa and Astra, other vehicles designed by GM (AMATUCCI; MARIOTTO, 2012). Another example is Fiat's New Uno model, which has parts and components from other Fiat vehicles. Circular air vents were inspired by the Fiat Doblo's design, while the instrument panel was developed based on the Fiat 500 compact. Other utilized parts are commands grouped on the left side of the driver (e.g. Punto) and the ceiling console (optional) inspired by the Fiat Idea minivan (QUATRO RODAS, 2010).

Interdependence between modules is a concept that is influenced by other conceptual elements, especially standardization and functionality. The modularization of a product means that it becomes decomposed into nearly independent modules, which makes possible the concurrent development of modules and components to be carried out autonomously by loosely coupled organizational structures (CAMPAGNOLO; CAMUFFO, 2010; PERSSON; AHLSTRÖM, 2006). Modules interact only between standardized interfaces (ZIRPOLI; BECKER, 2011b), because inconsistencies in this situation undermine coupling and connection between product modules, preventing their building as a whole. In terms of technical interdependencies, they must be structured before starting the design process rather than at the end of it; otherwise, product and process redesigns will be inevitable and costly to the company (ZIRPOLI; BECKER, 2011b). Suitably, the literature suggests that interdependencies between modules need to be developed during the early stages of product development and then transferred to the production processes, suggesting a direction of MID leading to MIP. Figure 7.2 illustrates the main concepts behind MID to MIP trajectory.

Figure 7.2 – Conceptual elements in the MID leading to MIP relationships



7.3.2.2 When MIP leads to MID

On the other hand, MIP might lead to or affect MID, since manufacturing structure might need to be taken into account before designing modular architecture. In this perspective, a certain type of product architecture is conditioned by the organizational capabilities of each company (RO et al., 2007), i.e., it is necessary to evaluate all productive processes' conditions and structure before establishing a redesign of a new modular product architecture.

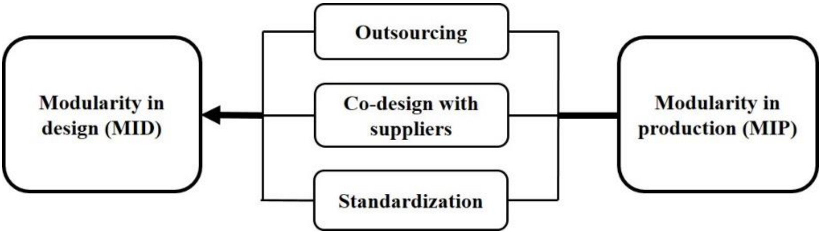
Regarding outsourcing, in the MIP leading to MID relationships, suppliers are usually involved in the manufacturing processes as well as in the initial stages of the product development process. In a broader way, changes in the hierarchies in production systems and/or inter-firm systems cause tension in their relationships with product architecture, thus encouraging the redefinition of product architecture (TAKEISHI; FUJIMOTO, 2003). The previous then, changes in inter-firm systems might lead to changes in product architecture (TAKEISHI; FUJIMOTO, 2003).

A practical example of more focus on MIP than MID is the Ford EcoSport's manufacturing unit (which also produces the Ford Fiesta model). This is characterized as an industrial condominium, an intermediate level between industrial districts and modular consortium (FRANCO, 2009). Salerno et al. (2009) report that this is one of the most advanced modular plants, and it is located two kilometers away from the engine and transmission manufacturers and most suppliers. In this case, Ford applies MIP concepts through the industrial condominium, where the automaker gathers its main suppliers around the factory, defining the modules produced, firming supply contracts, and sharing investments to be made and risks to be taken (FRANCO, 2009). This helps to become production processes more autonomous and independent, complying with MIP principles.

The most classical example is the full modular consortium in Resende, Brazil (CAUCHICK MIGUEL; PIRES, 2006; RAMALHO; SANTANA, 2002), which has a strong supplier integration with the automaker within the plant. Therefore, modularity's conceptual element "co-design with suppliers" is strongly evident in that case. The unique feature of the plant's production system rests on the relationship between the assembler (formerly VW; currently MAN Latin America) and its component suppliers. These firms were involved in a joint enterprise to establish a "modular system" of production. In this system, the component suppliers finance a part of the factory and organize the assembly of their components on site (RAMALHO; SANTANA, 2002). As such, the assembler has the main role of coordinating production and marketing the vehicle. Nevertheless, this is an example of commercial vehicles and not passenger cars where modularity tend to be a more complex issue due to a more integrated design (PERO et al., 2010; NOVAK; EPPINGER, 2001).

Standardizing interfaces as well as tolerances and product and module specifications are relevant in the MIP to MID perspective, as they assure that manufacturing processes are able to build the whole vehicle without (or with minimal) inconsistencies and that future recalls will be minimized. Furthermore, MIP needs standardization in order to favor process redesign and/or agile inclusion of new modules to meet product requirement changes (MIKKOLA, 2006). Figure 7.3 illustrates the main concepts when MIP affects MID.

Figure 7.3 – Conceptual elements in the MIP leading to MID relationships



7.3.2.3 Two-way trajectories between MID and MIP

Although some authors argue that the relationship can be either from MID to MIP or vice versa, MID and MIP can actually be a two-way trajectory. The relationships between product architectures and inter-firm systems are two-way – not only do the former influence the latter, but the latter also have some impact on the former (TAKEISHI; FUJIMOTO, 2003). In addition, the trajectories of causal relationships between modularity typologies depend on the unit of analysis considered (FIXSON; PARK, 2008). Corroborating this, differences in the trajectories of adopting modularity result from: (a) previous and current configuration of the industry in question; (b) different product characteristics; and (c) rate of technological change and organizational learning (FRIGANT; TALBOT, 2005).

In terms of the outsourcing concept, it can be made by: (i) designing modules and producing them in-house first, before outsourcing; (ii) outsourcing non-modular components before moving towards modular design; or (iii) simultaneously implementing modular design and outsourcing (Sako, 2003). Through these possibilities, one can observe that path 1 suggests modular design before considering modular production (through outsourcing modules and then more suppliers' involvement), while path 2 suggests outsourcing before structuring products in modules. Lastly, path 3 seems to have the greatest relationship between MID and MIP, since it deals with both modular design and outsourcing. In this context, it is still unclear whether MID leads to outsourcing or whether outsourcing of activities and components leads to MID (CAMPAGNOLO; CAMUFFO, 2010; 2009). Apparently, both ways might occur, depending on each context, objectives and project developed.

The local culture might affect these relationships. Module design may not happen within an organization with unified ownership, but both cultural and geographical proximity are important for the success of co-development (FUJIMOTO, 2008; TAKEISHI; FUJIMOTO, 2003; SAKO, 2003). Western companies are more likely to prioritize production modularity due to cost reduction through outsourcing, while Japanese companies prefer MID, relating it to MIP through functionality and quality conformity of modules as main criteria (PANDREMENOS et al., 2009). In addition, not only the local culture, but cars' architecture as well — since they differ substantially from model to model — affect production modularity. Moreover, the notion of mixing and matching, or sharing and reusing modules across models, never mind across OEMs, is not generally possible due to large variations in some modular product architectures (SAKO, 2003).

Through standardization, design specifications and the respective modules' tolerances are established during early stages of the product development process. Thus, standardization minimizes variability in manufacturing processes, a key aspect of lean manufacturing that can be facilitated by anticipating the inherent commonality of modular product architecture (JACOBS et al., 2007).

Figure 7.4 illustrates this trajectory and the main concepts involved. Table 7.2 summarizes the connections between MID and MIP, separated into consensus, differences, and also unexplored topics on modularity.

Figure 7.4 – Conceptual elements in the two-way MID and MIP relationships

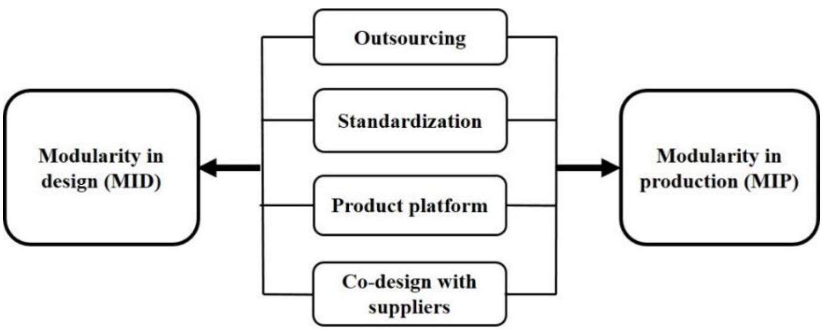


Table 7.2 – Summary of relationship between product and production modularity, consensus, differences and unexplored topics on modularity

	MID → MIP	**MIP → MID**	**MID ↔ MIP**
Relationships between product modularity and production modularity	- Higher degree of product modularity generates higher process modularity (JACOBS et al., 2011) - Product architecture serves as a "leverage" for engineering outsourcing (SANCHEZ; MAHONEY, 1996) - Modularity in production is an "inevitable result" of higher product modularity (BRUSONI; PRENCIPE, 2001) - Product structure influences its production (DATTA; ROY, 2010; PARALIKAS et al., 2011) - Modular products can facilitate organizational reconfiguration of companies (HOETKER, 2006)	- Certain type of product architecture is conditioned by the organizational capabilities of each company (RO et al., 2007) - Changes in the hierarchies in production systems and/or inter-firm systems cause tension in their relationships with product architecture, encouraging the redefinition of product architecture (TAKEISHI; FUJIMOTO, 2003) - Changes in inter-firm system might lead to changes in product architecture (TAKEISHI; FUJIMOTO, 2003)	- It is not clear yet whether product modularity leads to outsourcing activities or whether outsourcing leads to a higher or lower degree of product modularity (CAMPAGNOLO; CAMUFFO, 2009) - Western companies are more likely to prioritize production modularity due to cost reduction through outsourcing, while Japanese companies prefer modularity in design, relating it to production modularity through functionality and quality standardization of modules as main criteria (PANDREMENOS et al., 2009)

(continued...)

Table 7.2 (continued) – Summary of relationship between product and production modularity, consensus, differences and unexplored topics on modularity

	- Need to invest in acquiring appropriate technologies combined with appropriate design skills to enable higher modularity (XU et al., 2012)		- The trajectory of causal relationships between modularity typologies depends on the unit of analysis considered (FIXSON; PARK, 2008) - Differences in the trajectories of the adoption of modularity are results of: previous and current configuration of the industry in question; different product characteristics; and rate of technological change and organizational learning (FRIGANT; TALBOT, 2005) - The relationship between product architecture and inter-firm system is two-way – not only does the former affect the latter, but also the latter has some influence on the former (Takeishi and Fujimoto, 2003)

(continued...)

Table 7.2 (continued) – Summary of relationship between product and production modularity, consensus, differences and unexplored topics on modularity

	Consensus	Differences	Unexplored or little explored
Relationships between product modularity and production modularity / Connections between modularity	- Evidence supporting relationship between modularity in design and production. MID to some extent implies in MIP and vice versa - Product structure can generate technical and organizational impacts on manufacturing process of the supply chain as a whole - There are different levels of relationships between MID and MIP as well as different strategies and objectives by companies - There is a need for more empirical studies demonstrating the specific characteristics of MID and MIP relationships - Companies have different objectives when applying modularity in their products and processes	- Trajectory (direction) of product and production modularity relationships is not fully understood - Prevailing innovation degree (radical/incremental) that occurs through modularity	- Analysis of the relationships between modularity in design and production: technical and organizational aspects which are active and influential in these relationships - Analysis of the degree of product and production innovation resulting from modularity and the drivers and characteristics involved in the modularity/innovation relationships

7.3.3 Examples of MID and MIP relationships through conceptual elements

Attempts to increase the alignment and connections between modularity in design decisions with more modular, flexible and independent manufacturing processes have been carried out in the automotive industry. The following section presents three examples of efforts towards MID and MIP relationships. The examples have some variations among them. However, there are considerable similarities when analyzing what are the main conceptual elements and drivers involved that automotive companies have been exploring in MID and MIP connections. All cases are focused in passenger vehicles (not trucks and buses), which have more complexity in terms of applying modularity principles. The first case is Mercedes-Benz, company that focused primarily in standardizing production processes. The second example is the new product platform developed by Renault-Nissan, which explores common modules and components among various brands and vehicles. The third and last example is Volkswagen, which worked on reducing manufacturing lines and simultaneously build most product variants in fewer production lines as possible.

7.3.3.1 Example 1: Mercedes-Benz

Mercedes-Benz wants to control the Mercedes-Benz central plant and reduce production lines and production standardization costs. The group will organize their production in the future by product architectures. In organizational perspective, it reduces the power of the plant manager. Future managers will take the responsibility for production, where each one will be responsible for specific vehicle kits. However, this requires more flexibility. By standardizing and modularizing, the fixed costs are expected to fall. This should be possible by different vehicle variants from the same band pass and equipment used on several vehicle generations. Per year, the cost between 5% and 6% are expected to fall worldwide (MERCEDEZ, 2014).

Various vehicles should consist many equal parts as possible. The company's strategy faces that the sedans of the S, E and C-Class are based on a common rear-wheel drive architecture. There is also a front-wheel drive architecture for the complete compact car family, an architecture for SUV models, another for sports cars and an architecture for the drive train (MERCEDEZ, 2014).

To achieve these objectives, the company will manage to improve interface specifications in modular product development; and increase standardization in manufacturing processes by establishing more autonomous production modules and agile tooling for a different set of modules. In this context, the company explores standardization concept, in order to reduce setup modifications in manufacturing processes and increase flexibility to attend product variety demands. Additionally, functionalities, interfaces, and interdependence between vehicle modules will be managed to increase the standardization capacity of the manufacturing processes.

7.3.3.2 Example 2: Renault-Nissan (Common Module Family)

To better explore modularity, Renault-Nissan joint venture aims to extend the commonality concept through its product variants and modules by Common Module Family (CMF) platform. According to the Alliance, CMF is an engineering architecture that covers Renault/Nissan Alliance vehicles, from one or more segments, based on the assembly of compatible “Big Modules”: engine bay, cockpit, front underbody, rear underbody, and electrical/electronic architecture. This approach will focus on sharing standardized interfaces, modules and functions among various platforms (NISSAN, 2014; RENAULT, 2010). Therefore, a CMF is not a platform; it can involve several platforms. A platform is a horizontal segmentation; a CMF is a cross-sector concept (NISSAN, 2014), enabled by the “carry-across” concept (RENAULT, 2010).

In this case, the great objective is to combine various platforms, through the “carry-across” concept, to reduce lead-time and costs by standardizing manufacturing processes as a whole. Therefore, it seems that the focus is applying MID in CMF concept, in order to extend and share many modules and components as possible among various platforms, and then transfer this logic to MIP by standardizing production and building more autonomous manufacturing processes, but as a consequence of increasing commonality in modular platform architecture. Apparently, the Alliance explicitly establishes relationships between MID and MIP (exploring the MID to MIP trajectory). The main concern in CMF is regarding performance: since modules will be more common among brands, there is a risk of facing some issues when designing product performance.

7.3.3.3 Example 3: Volkswagen (MQB)

Volkswagen finished recently its new platform: the Modularer Querbaukasten (MQB), which aims to increase the predefined modules, in order to offer more different models and derivatives, maintaining the individual features of each vehicle (VOLKSWAGEN, 2014a). It will focus on increase standardized manufacturing process modules, underpinning all traverse-engined VW models (LUCARELLI et al., 2015). The focus will be in the more added-value modules (MELLO; MARX, 2007), such as the powertrain. VW has a unified engine assembly position for all engines to accept alternative powertrains, such as liquefied petroleum gas, compressed natural gas, electricity, gasoline, diesel as well as hybrid variants (CALLIANO, 2012). The main challenge VW is facing is to integrate and establish a satisfactory performance in the engine assembly module (in production): conflicts in terms of integrating tooling and setup have been generating issues when assembling the engine modules. Additionally, workers are facing difficulties with regard to understanding the building logic behind MQB (VOLKSWAGEN, 2014b).

In terms of MID, the company explores the modification of certain dimensions around some hard points, to increase balance proportions for future designs. This is enabled by designing some interfaces and variations among different brands, in order to facilitate further manufacturing lines standardization. In MIP perspective, MQB case suggests that it is the main VW focus. To increase product variations building in less manufacturing lines as possible, the company explores the standardization of the manufacturing processes, with the central objective of having a single platform that can derive 27 models for three brands (LUCARELLI et al., 2015). Thus, it seems that VW focuses more on MIP than MID, considering the main needs and objectives regarding the manufacturing processes prior to product design.

7.4 DISCUSSION

One of the main difficulties with identifying clear relationships related to modularity typologies in the automotive industry is the lack of clear concept definitions. Ro et al. (2007) report that a variety of terms is used in relation to modularity, which results in variations in understanding and interpretation within the sector. As an example, phrases such as “interchangeable parts,” “ability to mix and match,” “standardized interface,” and “planning platform” promote the reuse of a product's part of the product's family or generation while it "customizes" the other parts/components (RO et al., 2007). However, such conceptualization is not surprising, since modularity is a multifaceted concept. The variety of terms and lack of common definitions create additional issues with empirical studies and practical adoption of modularity in companies. Therefore, before conducting empirical research with companies, it is important to establish clear conceptual definitions of terms, such as "modules" and "systems".

In this study, it was found that there are, to some extent, clear connections between MID and MIP. Although some studies argue that it is possible to structure one modularity typology without necessarily influencing another, most papers consider that structuring modular product architecture has technical and organizational effects on production modularity and vice versa. In this sense, evidence suggests that usually product modularity is prioritized and later modularity concepts are used in production, simplifying manufacturing processes. This occurs especially with new products when designers and engineers have more autonomy to develop the product and/or platform architecture. In addition, literature addressing modularity in production is less developed than that of modularity in design (JACOBS et al., 2011), which suggests more decisions from MID to MIP. Additionally, it was noticed that relationships between MID and MIP can be stronger if managers and engineers involved have a mature knowledge about modularity principles and concepts, considering not only technical aspects but also strategic and mid- and long-term goals.

In this scenario, as presented in the previous section, some automakers are making significant efforts with regard to vehicle architecture variations. In the coming years, Mercedes (2014) plans to organize various production processes by product architectures. This future organization suggests an interesting and even ambitious direction towards MID and MIP relationships since each specific vehicle will have specific production requirements. Then, it seems that this modularity approach will focus on creating new architectural knowledge in the development of improved interface specifications (SANCHEZ, 2013). Renault-Nissan also intends to achieve better alignment between MID and MIP, but in a different trajectory. Nissan (2013) states that the Common Module Family (CMF) will extend manufacturing "communalization" to a higher number of vehicles developed within the Alliance (Renault-Nissan). Apparently, the focus in this approach is to reduce time to market and product and production costs with a greater level of commonality through more modules and components that are common (SANCHEZ, 2013).

Through its MQB platform, Volkswagen will be able to make much greater use of predefined modules than before in terms of offering different models and derivatives, without inhibiting each brand's individual nature and each car's characteristics (VOLKSWAGEN, 2014), seeking to increase product variety at low costs and reduce product costs (SANCHEZ, 2013). In addition, this new platform can provide both greater standardization and flexibility for the new models to be developed by VW (VOLKSWAGEN, 2014).

However, in spite of the effective strategic use of modularity by a few automotive firms (as some examples previously exposed), in the automotive industry generally there is still comparatively limited understanding of what modular strategies really mean and of the organizational changes necessary to implement modularity strategies effectively. In effect, there is evidence that at least some automotive firms have not yet fully grasped the potential strategic uses of modularity or the organizational and process transformations necessary to implement modularity strategies effectively (SANCHEZ, 2013).

Companies more concerned in the implementation of modularity can increase the effects in firm flexibility, resource allocation and transfer knowledge, having an impact on modularity in design decisions (PARENTE et al., 2011). Nevertheless, it is suggested that some principles must be comprehended in order to create a better organizational environment to improve companies' capacities to obtain modularity benefits as well as to minimize its possible drawbacks. Then, would be possible to facilitate MIP through MID (JACOBS et al., 2011). In this sense, and also based on the framework suggested by Sanchez (2013), which proposes a modularity maturity model (MMM) for companies to evaluate their level of application of modularity, considering as main criteria the focus on design and development activities and the level of management understanding about the modularity concept (refer to Table 7.3), the following proposition was built:

Proposition 1: Relationships between MID and MIP are stronger if the company has a higher maturity level when applying modularity principles.

Table 7.3 – Modularity maturity model (Sanchez, 2013)

Maturity level	Management understanding	Design and development activities
7	Modularity as framework for *identifying and developing new strategic competences*	Architectural management function is directly involved in *identifying goals for strategic competence development*
6	Modularity as framework for *strategic integration*	Architectural management function is directly involved in *setting market, technology, and business strategies*
5	Modularity as framework for *knowledge management*	New architectural knowledge created in development is captured in *improved interface specifications*
4	Modularity seen as means to *reduce time to market*	Modular development process based on “new rules and new roles” enables *concurrent component development*
3	Modularity seen as means to *increase product variety*	*Strategic partitioning* decouples stable from variable components to enable low-cost configuration of product variations
2A and 2B	Modularity seen as means to *reduce product costs*	Early form of modular development process seeks to design (2A) *common components* and (2B) *reusable components*
1	Modularity seen only as *engineering issue*	Conventional development process uses *technical modularity* to moderately reduce design time and cost
0	Unaware of modularity	Conventional development process makes no systematic use of modularity

In addition, the different approaches that automotive companies are taking (as discussed in section 3.2) confirm that OEMs’ motives for adopting modules are multiple, and different motives lead to varying degrees of the push for outsourcing modules (SAKO, 2003). Ten years later, Sanchez (2013, p. 213) corroborates: “In the automotive industry today, it is evident that different firms are pursuing different priorities in the way they strategically partition their vehicle architectures." In this context, one can observe that the direction of the trajectory between MID and MIP reflects the priorities that companies will have about their product and production development. It is suggested that MID leading to MIP indicates that companies prioritize the product design and its variants before modularizing the production process. On the other hand, modularizing production lines indicates a preference in reducing production costs and lead-time before the product design itself. In this case, it seems that modularity implementation is not as mature as in developing MID before MIP.

This paper shows that the different trajectories have different concepts leading to the application of modularity. Therefore, one can clearly relate modularity in design to production by using specific conceptual elements that are extensively adopted when researchers and practitioners work with modularity. In addition, there is potential to establish cause and effect relationships between these two modularity typologies (product and production). Nevertheless, it depends on the unit of analysis investigated, since conceptual elements might be explored in different ways according to the needs and focus of the company. Commonality, product variety, suppliers' involvement, and outsourcing are the most highlighted concepts regarding the potential to build causal relationships between modularity in design and production. Moreover, in order to obtain increased relationships between MID and MIP, companies must consider issues not only in technical terms, but also in strategic terms, establishing clearly what objectives they want to achieve through adoption of modularity, in order to enhance its benefits (cost and lead-time reduction, higher product variety, innovation in product and production, etc.). Additionally, a modular design can vary according to a specific objective and timing of product development, i.e. each product can be modularized with different aims depending on the product life-cycle phase the product is passing through. In this sense, it seems reasonable that different trajectories correspond to different objectives and consequently to different results (CAMPAGNOLO; CAMUFFO, 2010); therefore:

Proposition 2: Relationships trajectories between MID and MIP are deeper if a company clearly defines its modularity decisions and objectives previously.

7.4.1 Conceptual elements influencing MID and MIP relationships

Some aspects of MID and MIP relationships emerged as relevant and able to establish connections between the two modularity typologies usually applied in the automotive industry. Additionally, some conceptual elements might be connected to each other. Literature analysis suggests that most of the conceptual elements found have more focus on MID than in MIP.

Through outsourcing strategy, companies can improve their economies within their design activities and explore possible external sources of innovation, both in design and production, when suppliers have higher manufacturing capabilities. Thus, outsourcing can also affect modular production since transferring design and assembly activities to suppliers might enhance agility and autonomy in production due to more autonomous processes, as well as reducing complexity when managing the supply chain. Thus, it increases the possibility of applying the outsourcing principle, which in turn reduces the investment required for industries and complexities among production operations.

Product variety is developed during modularity in design decisions, aiming at offering a product variation that will attend current market demands, i.e., through modularity in design, it is possible to increase product variety. Such decisions, to some extent, might affect modular production since manufacturing systems need to be (re)designed in order to become more flexible to generate all variants from a given product platform. Depending on the product variation, production configuration, and machinery setup will be significantly modified.

Commonality concept is reflected in the components and architectural structure and is normally connected to modular design decisions in terms of what modules, parts, and components will be shared among a certain number of vehicles/brands. Additionally, commonality is built by standardizing modules interfaces and dimensions. It suggests that commonality and standardization are tightly connected. That standardization enables the connection of MID to MIP because the standardized and common modules/components might facilitate machinery standardization (setup) and autonomy to produce more modules in less manufacturing lines and equipment settings. Then, standardization can be connected to MIP enabling the building of more vehicles and modules with fewer production settings as possible.

Functionality is a concept intrinsically connected to MID. However, its technical-oriented characteristic impacts product components and interactions. Back to Sandero’s case, function definition lead to a delegation of modules' design and manufacturing to suppliers, which also suggests a connection between functionality and co-design with suppliers. Such decisions affect MIP in an indirect way. In the case of a product's modular architecture, a one-to-one mapping takes place from the functional elements in the functional structure of the product's physical components and specifies the decoupled interfaces between components. Then, from the components' architecture, other decisions (e.g. commonality, outsourcing) might impact on MIP features.

Product platform is a strategy adopted by firms in a multi-project context, focused on reducing lead-time and costs, enhancing reliability and allowing more manufacturing flexibility. It is a large set of product components with standardized interfaces that are physically connected to a stable subset of a larger product and that can be shared among different final products. By analyzing literature on product platform, it is suggestive that this is a broader conceptual element that considers most of the previous concepts, since decisions about product functionalities and modules' interdependence, common modules and components, product variety and which modules will be outsourced and/or co-designed together with suppliers, can be made through product platform strategy. Lastly, Table 7.4 presents the most cited conceptual elements from the literature, followed by a description of how each conceptual element acts according to relationships trajectory between MID and MIP.

Table 7.4 – Modularity’s conceptual elements and their MID and MIP connections

Conceptual element	Summary description	Prevailing relationship trajectory	References
Outsourcing	- Transferring engineering and/or assembly activities to suppliers - Design capabilities and/or production capabilities can be taken into account - Modularity increases the possibility of outsourcing, which might reduce the investment required for industries and complexities among production operations - Some components might be already outsourced and manufactured by suppliers, and this scenario might influence modularity in design decisions in terms of changing the current suppliers, which can affect both production and product decisions (which supplier will develop what module(s))	**MID ↔ MIP**	Brusoni and Prencipe (2011); Zirpoli and Becker (2011b); Shamsuzzoha et al.(2010); Ro et al. (2007); Mikkola (2003); Collins et al. (1997); Sanchez and Mahoney (1996)

(continued...)

Table 7.4 (continued) – Modularity's conceptual elements and their MID and MIP connections

Standardization	- Makes it possible to recombine the components of products without an elaborate adaptation of interfaces - Standardized interfaces enables the production of a large number of end items through the reconfiguration of a comparatively smaller set of inputs - In the production perspective, standardized groups characterize production modules. This enables the possibility of fewer settings change in machinery even with more product variations - Standardized production processes might be considered when modularity in design is developed: production might have limitations in some capabilities and machinery settings that can affect design decisions	**MID ↔ MIP**	Park et al. (2012); Jacobs et al. (2007); Mikkola (2006); Brusoni and Prencipe (2001); Baldwin and Clark (1997)
Commonality	- Determines the level of modules/components that are common to different products - Commonality is built through standardization, and it is reflected in the components and architectural structure - Earliest studies dealing with product modularity expressed this concept in terms of component commonality across a given assortment of products - Through commonality, companies can enable the processing flexibility of machines, and in turn, the agility of a manufacturing system - Sharing common modules contributes to MID and MIP relationships	**MID → MIP**	Pasche and Sköld (2012); Jacobs et al. (2011); Fixson (2007); Zwerink et al. (2007); Watanabe and Abe (2004); Fisher et al. (1999)

(continued...)

Table 7.4 (continued) – Modularity's conceptual elements and their MID and MIP connections

Functionality	- Ability or capacity of performing a task or function - Modules/components of a product may have one or more functionalities according to the product design - A one-to-one mapping takes place from the functional elements in the functional structure of the physical components of the product and specifies the decoupled interfaces between components	**MID → MIP**	Sushandoyo and Magnusson (2012); Park et al. (2012); Pandremenos et al. (2009); Mikkola (2006); Baldwin and Clark (2000)
Product variety	- Enables variety offering of products that the company makes available in the market - The larger the variety, the greater is the possibility of offering product diversity - Modularity in design enables the easy generation of product families from a basic platform design, by simply mixing and matching the various modules - Through modularity in design, it is possible to increase product variety - Manufacturing processes, as consequence, have equipment and machinery adjustments in order to enhance flexibility and agility to build all variants developed in modularity in design	**MID → MIP**	Zeppini and Van der Bergh (2013); Liu et al. (2010); Pil and Holweg (2004); MacDuffie et al. (1996).

(continued...)

Table 7.4 (continued) – Modularity's conceptual elements and their MID and MIP connections

Interdependence between modules	- Degree of structural independence the modules/components have among themselves - The modularization of a product means that it becomes decomposed into nearly independent modules, which makes possible the concurrent development of modules and components to be carried out autonomously by loosely coupled organizational structures - Interdependence between modules can be enabled by functionality and standardization decisions, other intrinsic concepts of modularity - The more independence they have, the more coupling and uncoupling autonomy and capacity the modules have, while still being able to work together as a whole	**MID → MIP**	Park et al. (2012); Zirpoli and Becker (2011b); Baldwin and Clark (2000)
Co-design / Co-development with suppliers	- Refers to the degree of suppliers' involvement in product development - Suppliers involved in earlier phases of the product development process tend to have more influence in the product architecture definitions - Modular product design is beneficial in solving the task of coordinating suppliers as they independently develop components and systems that need to be integrated physically (thanks to standardized interfaces)	**MID ↔ MIP**	Zirpoli and Becker (2011b); Salerno et al. (2009); Campagnolo and Camuffo (2009); Ro et al. (2007)

(continued...)

Table 7.4 (continued) – Modularity’s conceptual elements and their MID and MIP connections

Product platform	- A large set of product components with standardized interfaces that are physically connected to a stable subset of a larger product and that can be shared among different final products - Reduces the lead-time and the development cost, it enhances the product quality and reliability, it allows variety and mass customization and finally it increases manufacturing flexibility - Central strategy for companies to handle agile manufacturing and new product development, which incorporate several approaches - Product platform concept may combine various modularity concepts, such as: - Functionality (function definitions according to each module and its position in the platform) - Standardization, commonality (decision of common modules and components along a variety of vehicles, brands, and models) - Product variety (level of variety of vehicles and brands, and level of component and module variety) - Co-design and outsourcing (selecting suppliers and selecting their level of involvement in product development process and production decisions and demands)	**MID ↔ MIP**	Pasche and Sköld (2012); Mahmoud-Jouini and Lenfle (2010); Zhang and Huang (2010); Hsuan and Hansen (2007); Sköld and Karlsson (2007)

7.5 CONCLUDING REMARKS OF THIS CHAPTER

This paper offers three main contributions: it (i) establishes in a systematized way the relationship trajectories between MID and MIP, (ii) analyzes the specific conceptual elements involved in MID and MIP relationships, and (iii) offers two propositions on how these cause and effect relationships can increase practical relevance. Considering that relationships between MID and MIP vary according to each company's context, one can propose that the trajectories of building MID and MIP depend on the focus of each OEM, as well as on the context where they are involved and the focus of the vehicle under development.

As for theoretical contributions, this study shows a systematic presentation of MID and MIP relationships through some conceptual elements found in the literature that have a connection and/or are premises for adopting modularity. It shows that it is not possible to establish only a one-way connection between MID and MIP, considering that these relationships have conceptual elements that affect both product and organizational architecture. The importance of these connections is dependent on what companies prioritize more (MID or MIP). Furthermore, literature is still not well developed concerning relationships and directions between MID and MIP. There are still more issues to be explained, and the conceptual elements involved in these relationships can be a way of demonstrating how MID and MIP are related.

To both scholars and managers, this paper might help towards a better modular product and production planning. From the literature and automotive examples, one can find that some companies did not obtain more modularity benefits because they plan modularity in design without taking into account further implications in manufacturing processes. Thus, it is suggested that analyzing modularity concepts and objectives to establish MID and MIP relationships might be important to increase modularity advantages. In addition, the MID and MIP relationships representation exposed in this study might be important to new product development, since relevant concepts regarding modularity can be developed and planned prior to implementing both modular product architecture and production.

This study constitutes one-step towards enhancing the theoretical and practical foundations for research on modularity and the relationships between MID and MIP, and it obviously has limitations. Firstly, the findings are somewhat specific to the examined industry (automotive). Secondly, since this study is a theory-building effort, further empirical study is needed for answering questions such as How are these causal relationships able to provide modularity benefits or generate drawbacks? and What are the main aspects to consider when aiming for higher integration between MID and MIP, in order to obtain more interaction between product architecture and manufacturing structure? Further research will develop and conduct multiple case studies. Some interesting insights about the practical implications of MID and MIP relationships might emerge through this next step. In addition, there is still need for testing the propositions, in order to analyze whether they are coherent with literature in a practical perspective. Hence, the next chapter presents the empirical investigation that aimed to verify the conceptual framework developed in this thesis, through a case-based research in two car manufacturers placed in Brazil.

8 RELATIONSHIPS BETWEEN MODULARITY IN DESIGN AND PRODUCTION: A FIELD STUDY OF TWO AUTOMOBILE MANUFACTURERS

This chapter presents the contents of the last paper of this thesis[19]. It culminates in an empirical investigation in two car manufacturers at Brazil, in order to verify the theoretical framework application and further adjustments according to each automaker context. The following chapter also demonstrates why and how automotive companies establish MID and MIP relationship and points out some contingent factors.

8.1 INTRODUCTION

Passenger cars are the third most traded manufactured good worldwide and one of the most complex products (OEC, 2015). The automotive is one of the most competitive industries in terms of technology and stakeholders involved in the innovation process (HOLWEG, 2008). In order to improve managerial decisions to better deal with this complexity, the concept of modularity was adopted and since then it has been widely used by the automotive sector, gaining importance in manufacturing firms in this industry (SHAMSUZZOHA et al., 2010). However, despite this wide application, there are still many challenges to overcome about modularity in this industry (LUCARELLI et al., 2015; SANCHEZ, 2013; ZIRPOLI; BECKER, 2011b). Like any other strategies and methods, decisions about design modularity and production processes significantly affect cars' project development costs; thus, it seems that modularity has a significant impact in the automotive industry (PANDREMENOS et al., 2009).

Within this scenario, an important issue has raised (LUGO-MÁRQUEZ et al., 2016; LUCARELLI et al., 2015; JACOBS et al., 2011; CAMPAGNOLO; CAMUFFO, 2010): the relationships between modularity in design (MID) and modularity in production (MIP). As many automotive firms are applying MID and MIP relationships concept to analyze how those relationships affect efficiency and competitiveness, it has begun to attract scholars' attention. However, research on how MID and MIP are related to one another is still limited, even though prominent research stress the importance of this topic (e.g., LUGO-MÁRQUEZ et al., 2016; LUCARELLI et al., 2015; JACOBS et al., 2011;

[19] This is a working paper to be submitted to Production Planning & Control (B1 – Qualis-Capes).

CAMPAGNOLO; CAMUFFO, 2010; SCHILLING; STEENSMA, 2001). Furthermore, practical cases include Mercedes-Benz's new product platform management, Renault-Nissan's Common Module Family (CMF) platform and Volkswagen's Modularer Querbaukasten (MQB) platform (LUCARELLI et al., 2015; MERCEDES-BENZ, 2014; VOLKSWAGEN, 2014; RENAULT-NISSAN, 2013; CALLIANO, 2012). There is also evidence that companies are adopting product modularity to enhance strategic and operational flexibility (SHAIK et al., 2015; PASCHE; PERSSON, 2012), which also might affect manufacturing processes.

Moreover, research on MID and MIP relationship points in different directions. In some cases, it seems that MIP is an unavoidable result of MID decisions (BRUSONI; PRENCIPE, 2001), i.e. the modular product structure of a vehicle or a whole vehicle platform influences its production (DATTA; ROY, 2010). Therefore, a production system that is capable of producing responsibly all vehicle variants is required (PARALIKAS et al., 2011). Yet, product modularity may drive process modularity because the firm configures its production process to match product architectures; that is, a conscious choice is made to align manufacturing priorities with design choices (JACOBS et al., 2011). Thus, redesigning products through modularity may lead to changes in the production structure (LUGO-MÁRQUEZ et al., 2016). On the other hand, there is evidence that MIP can be developed without necessarily designing the product through MID (RODRIGUES et al., 2012).

The trajectories of MID and MIP relationship and respective organizational effects depend on the unit of analysis considered (FIXSON; PARK, 2008). In this context, it is not clear whether MID determines outsourcing or outsourcing activities and decisions affect MID (CAMPAGNOLO; CAMUFFO, 2009). Therefore, it is important to take up the challenge of adopting a comprehensive approach and include an analysis of how modularity may affect the simultaneous design of products, production systems, and organizations (CAMPAGNOLO; CAMUFFO, 2010), because modularity is an appealing design approach that supports vehicle manufacturers, and through the application of different interchangeability technologies, involves both production processes and products (LUCARELLI et al., 2015).

Research conducted previously (e.g. LUCARELLI et al., 2015; SANCHEZ, 2013; JACOBS et al., 2011; CAMPAGNOLO; CAMUFFO, 2010; FIXSON; PARK, 2008) found that the existing literature does not offer yet a satisfactory answer to the question how modularity in design and production are related (and leads from) to one another; and how the main conceptual elements involved in those relationships connect MID and MIP as well as the possible benefits and limitations. Thus, this study proposes the following research questions:

- RQ1: In car manufacturers, what leads from one to another in MID and MIP relationships?
- RQ2: How each modularity's conceptual elements guide product development decisions regarding MID and MIP relationships?
- RQ3: How MID and MIP relationships contribute to potentialities or generate limitations in manufacturing processes that affect modular design decisions (and vice versa)?

In order to answer the research questions, the paper investigates MID and MIP relationship as well as the main benefits and drawbacks behind them. The paper is organized as follows. It firstly describes the theoretical framework developed to analyze MID and MIP relationship in the investigated companies, followed by the research design to conduct the field study. The paper ends presenting its findings, discussion, and conclusions.

8.2 THEORETICAL BACKGROUND ON DESIGN AND PRODUCTION MODULARITY AND THEIR RELATIONS

Before presenting the theoretical evidence regarding MID and MIP relationship, it is important to state explicitly what are the concepts taken into account regarding MID and MIP. Modularity in design (MID) is the product design defined through a system that can be decomposed in various subsystems with a high degree of interdependence among them (BALDWIN; CLARK, 2000; 1997). Such interdependencies are facilitated by standardized interfaces, which allow the clear definition of module's functionality and permits the building of reconfigurable modules and components to offer more product variety at lower design and manufacturing costs (CABIGIOSU et al., 2013; SANCHEZ, 2013; JACOBS et al., 2011; FIXSON, 2007; SCHILLING; STEENSMA, 2001; BALDWIN; CLARK, 2000; BALDWIN; CLARK, 1997; SANCHEZ; MAHONEY, 1996; ULRICH; EPPINGER, 1995).

Meanwhile, modularity in production (MIP) is the organization of production through standardized systems that facilitate production reconfiguration, greater application of the same machinery and settings for a high variety of manufactured products (JACOBS et al., 2011). It allows greater flexibility in production, and enables more autonomous and independent processes, characterizing production as modular, with some activities having the possibility of being transferred to suppliers (LUCARELLI et al., 2015; SANCHEZ, 2013; JACOBS et al., 2011; PERSSON, 2006; FINE et al., 2005; Sako, 2003; SCHILLING; STEENSMA, 2001; HOOGEWEEGEN et al., 1999). Commonly, the automotive industry applies MIP aiming at three main objectives (LUCARELLI et al., 2015): reduce costs, increase flexibility and reduce the complexity of manufacturing activities. Table 8.1 summarizes the main characteristics of MID and MIP.

Table 8.1 – Main modularity characteristics in design and production based on literature

Modularity Typology	Main characteristics
Modularity in Design (MID)	• System that is decomposable into various subsystems • High interdependence between systems/modules • Standardized interfaces • Reconfigurable and reusable modules • Allows product variety at low costs
Modularity in Production (MIP)	• Standardized production systems • Easy production reconfiguration • More common machinery settings to various manufactured products • Greater production flexibility • More autonomous/independent processes • Less production complexity

Previous studies (e.g. LUGO-MÁRQUEZ et al., 2016; LUCARELLI et al., 2015; SANCHEZ, 2013; PARALIKAS et al., 2011; JACOBS et al., 2011) have suggested that relationship between MID and MIP (one leading to another) might be relevant in terms of, for instance, coordination of activities between product design and manufacturing processes. Some evidence found in the literature suggests causal relationship from MID to MIP. Sometimes modularity in production might be understood as an inevitable result of higher modularity in products since the product structure affects its production, which might facilitate organizational reconfiguration of companies (PARALIKAS et al., 2011; DATTA; ROY, 2010; HOETKER, 2006; BRUSONI; PRENCIPE, 2001). To support this trajectory, it has been argued that modularity decisions during design phases of the product development processes affect further decisions and activities regarding manufacturing processes, enabling MIP (e.g. LUGO-MÁRQUEZ et al., 2016; JACOBS et al., 2011; SAKO, 2003; SANCHEZ; MAHONEY, 1996). As such, modular products call for modular organizations, and this correspondence is beneficial for enhancing organizational flexibility, eliminating the need for hierarchical coordination and reducing complexity (SAKO, 2003).

In some cases, MIP might lead or affect MID decisions. For instance, manufacturing structure might need to be taken into account before designing modular architecture (e.g. RO et al., 2007; SAKO, 2003; TAKEISHI; FUJIMOTO, 2003). In this perspective, a certain type of product architecture is conditioned by the organizational capabilities of each company (RO et al., 2007), i.e. it is necessary to evaluate all productive processes' conditions and structure before establishing a redesign of a new modular product architecture. Changes in the hierarchies in production systems and/or inter-firm systems cause tension in their relationship with product architecture, encouraging the redefinition of product architecture (TAKEISHI; FUJIMOTO, 2003).

However, there are instances when MID and MIP relationship can have a two-way trajectory (e.g. FIXSON; PARK, 2008; FRIGANT; TALBOT, 2005; TAKEISHI; FUJIMOTO, 2003; SAKO, 2003). This means that not only the former affects the latter, but also the latter has some influence on the former (TAKEISHI; FUJIMOTO, 2003). Modularity in this sense can affect both product design and production processes (LUCARELLI et al., 2015). This may occur when it is not certain whether product modularity determines outsourcing or outsourcing activities and tasks affect product modularity (CAMPAGNOLO; CAMUFFO, 2009). Normally, Western companies are more likely to prioritize production modularity due to cost reduction through outsourcing, while Japanese companies prefer modularity in design, relating it with production modularity through functionality and quality standardization of modules as main criteria (PANDREMENOS et al., 2009).

Furthermore, differences in the trajectories of modularity adoption result from (FRIGANT; TALBOT, 2005): (i) previous and the current configuration of the industry in question; (ii) different product characteristics; and (iii) rate of technological change and organizational learning. Accordingly, the trajectory of causal relationships between modularity typologies depends on the unit of analysis considered

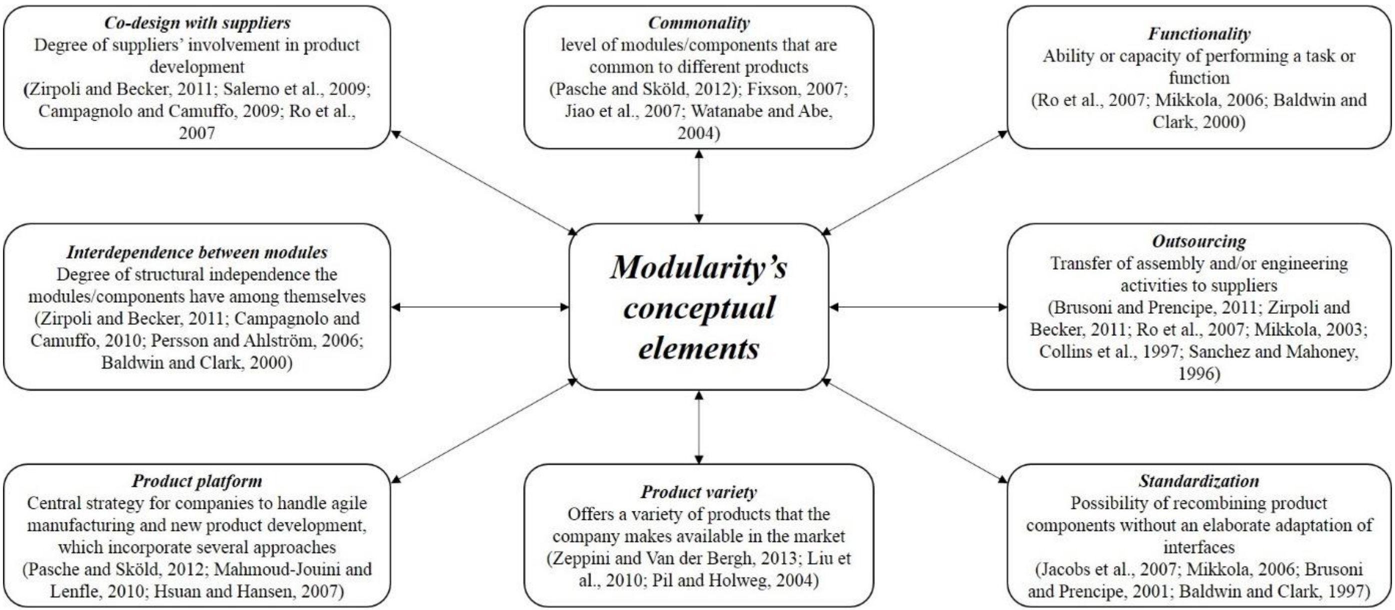
(FIXSON; PARK, 2008). Thus, there are three possibilities involved in MID and MIP relationship: concepts leading from MID to MIP, from MIP to MID or concepts affecting MID and MIP in both ways.

Hence, there seems to exist a relevant research gap in modularity topic, which is to analyze the implications in MID and MIP relationship and what leads from one to another. It is important to take up the challenge of analyzing with a comprehensive approach how modularity may affect the simultaneous design of products, production systems, and organizations (CAMPAGNOLO; CAMUFFO, 2010). Consequently, the impact of modular product architecture in manufacturing processes emerges as an interesting opportunity for future research. To date, there has been some contrasting evidence regarding modularity application in the automotive industry (Cabigiosu et al., 2013). In this context, there are conceptual elements that lead MID and MIP from one to another. Those are presented next.

8.2.1 MID and MIP conceptual elements

To identify the conceptual elements that connect MID to MIP and vice-versa, this study identified publications in peer-reviewed journals that are related to modularity and the automotive industry, besides showing evidence about the concepts connecting MID and MIP from one to another. This yielded 61 papers relating modularity in the automotive industry. Within those papers, the study searched for concepts and contents that illustrated modularity definitions and how it was applied in each publication, based on Bardin’s (2011) guidelines on how to conduct a content analysis: organization, coding, categorization, and inference.
Through this search, it was possible to identify that modularity in MID and MIP decisions are based on conceptual elements (Figure 8.1) that are directly related to design and processes structure such as co-design with suppliers, commonality, functionality, interdependence between modules, outsourcing, product platform, product variety and standardization.

Figure 8.1 – Modularity’s conceptual elements



The first concept is the co-design with suppliers. MID has direct and indirect effects on costs, and the indirect effects are the result of the higher suppliers' integration and integration between product design and manufacturing (JACOBS et al., 2007). With such integration, suppliers' involvement in product design may intensify MID and MIP connections, since suppliers will not only be involved in assembly processes, but also in the design phases of the product development process.

Commonality is more common in products than processes, and consists of using identical components in different products (FIXSON, 2007). This concept is characterized by grouping similar module variants to generate similar variations of a specific module type (JIAO et al., 2007; WATANABE; ANE, 2004). In this sense, specifications must be visibly defined to avoid inconsistencies connecting product modules and components. This suggests that commonality has also a strong connection with standardization of product interfaces, modules, and components.

Functionality enables the building of physical modular arrangements and their connections within the "systems" (RO et al., 2007). It permits to establish how modules will be composed according to the vehicle architecture and modules and subsystems functions that will compose the whole vehicle. Furthermore, it is possible to associate the functions, modules and the respective suppliers that will be responsible for each module to be designed and manufactured.

By exploring outsourcing strategies, automakers may increase economies on design activities and explore possible external sources of innovation in both design and production (CABIGIOSU et al., 2013). Thus, outsourcing can also affect MIP since transferring design and assembly activities to suppliers may enhance agility and autonomy in production due to more autonomous processes (ZIRPOLI; BECKER, 2011b). This may increase the possibility of applying outsourcing principles, which reduces the investment demanded and manufacturing processes' complexity.

Standardization aims to establish design specifications and the respective modules' tolerances during early stages of the product development process. This conceptual element helps to minimize variability in manufacturing processes, a key aspect of lean manufacturing that can be facilitated by anticipating the inherent commonality of modular product architecture (JACOBS et al., 2007). Thus, standardization relates to commonality and is crucial to building common modules among various car models.

In product variety concept, the ready configurability of new product variations within a modular architecture substantially improves an organization's ability to offer greater variety to the market (SANCHEZ, 2013). Through modular product architecture, it is possible to achieve product variants at lower costs (STONE et al., 2000). Especially in the automotive industry, product variety is explored in the platform dimension in order to create flexibility in product architectures, where a product can be designed through versatile modules, common parts and geometries, and standardized interfaces (WATANABE; ANE, 2004).

Product platform consists of a large set of product components with standardized interfaces that are physically connected as a stable subset of a larger product and that can be shared among different final products (MAHMOUD-JOUINI; LENFLE, 2010). One of the major challenges when designing platforms is to balance commonality and product differentiation, because emphasizing commonalities reduces design and production costs and delay, while hampers product diversity used in the platform (HSUAN; HANSEN, 2007). Thus, product platform is a concept that combines both design and manufacturing strategies and decisions in its creation.

Lastly, the modularization of a product means that the product becomes decomposed into nearly independent modules, which makes possible the concurrent development of modules and components to be carried out autonomously by loosely coupled organizational structures (CAMPAGNOLO; CAMUFFO, 2010; PERSSON; AHLSTRÖM, 2006). In addition, interdependence between modules is a concept that can be affected by other conceptual elements, such as standardization and functionality. The more independence modules have, the more coupling and uncoupling autonomy the modules will obtain, however, this is a challenge in vehicle design since their product architectures tend to be prevalently integral (CABIGIOSU et al., 2013; MACDUFFIE, 2013).

Given the inherent characteristics of modularity, grasping on understanding modularity may be important to overcome challenges and obstacles that are intrinsic to the automotive industry (LUCARELLI et al., 2015) as well as to redesign products and consequent changes in manufacturing processes (LUGO-MÁRQUEZ et al., 2016). Next section presents the research methods to conduct this study.

8.3 RESEARCH METHODS

It is the aim of this paper to explore a research gap on modularity relations in the context of the automotive industry. The units of analysis in this paper are the modular design activities and decisions and the modular production planning and processes (as well as the consequences of MID and MIP on one to another) of the investigated companies. The automotive industry was selected as the object of analysis due to its intense competition (HOLWEG, 2008) where platform and modularity are means for creating customization and variety.

Automobile firms need to change and learn constantly about their products and processes in order to attend market demands, and modularity might be important in this learning process (WAGNER et al., 2015), especially due to its complexity in product platform design and assembly. Yet, little is developed about the implications of product architecture on organizational design in the automotive industry and it is important to understand the possible integration mechanisms that enhance more connections between modular product architecture and modular production (LIAO et al., 2013; RO et al., 2007), approaches that have been explored by car manufacturers.

In this context, case-based research was adopted in order to contribute to this research gap, deepening the understanding of MID and MIP relationship in two car assemblers. Case studies may support researchers towards seeing new theoretical relationships and question old ones (PERSSON; AHLSTRÖM, 2006; DYER, 1991). Additionally, the case-based approach was chosen because the research questions of this study embody an explanatory component (as recommended by YIN, 2014 and VOSS, 2009) and it is a well-suited approach for questions that are not thoroughly researched (PERSSON; AHLSTRÖM, 2006).

To enhance further data analysis, the cross-case analysis was applied (STAKE, 2006). This approach helps to deepen understanding and explanation (MILES; HUBERMAN, 2014), compare the phenomena investigated in both companies (YIN, 2014), and identify common and particular aspects between cases (STAKE, 2006). This can also cast light on the impact of different decisions and approaches regarding the subject, and finally to prevent researcher bias (VOSS, 2009). The selection of the investigated companies was conducted following criteria that were built based on literature (as recommended by SOUSA; VOSS, 2001) concerning modularity as well as practical cases involving some car manufacturer. Firstly, a broad overview was conducted in order to identify and analyze the automotive projects that showed evidence of applying modularity principles in their design and/or production processes. This step showed that there were some relevant vehicles developed locally, with modularity concepts emerging as a common and relevant strategy adopted for both design and production processes. Modules' definition by functionalities, extended commonality in parts and modules and standardized manufacturing processes and systems were some of the important decisions that guided those car manufacturers.

Next, the study had to identify companies for conduct the empirical investigation, by using the following criteria for selecting them: (i) have proximity with suppliers to develop modules and/or parts; (ii) have maturity and experience applying modularity; (iii) apply both modularity in design and in production; and (iv) have open access for gathering data. Afterward, a draft list of six companies was compiled. Then, the authors started soliciting participation on the most promising companies from that list. In this process, those plants that declined participation were replaced by the next promising plants. Thus, by the end of this process, the final sample was only composed of two companies that accepted to open access for data collection, even though with some restrictions, such as not tape recording the conversation in one of the companies and unavailability of visiting the manufacturing processes in the other plant.

8.3.1 Data collection procedures

This study used multiple sources of evidence in order to increase construct validity. Firstly, the companies filled in a questionnaire in order to collect general information regarding modularity as well as its application focus. The goal was to gather general practices with regard to modularity that would establish a preliminary relationship between MID and MIP. Typical questions included "how is product architecture defined by the company?" and "what are the main objectives when applying modularity?", among others. Then, it was possible to have a preliminary understanding about the application of modularity concepts in those firms, the main implications, changes, benefits, and drawbacks.

Before contacting the company, the authors created and developed an interview protocol, further revised by an academic expert. This helped to increase protocol's precision and cohesion in terms of clarity and relevance. After that, five semi-structured interviews with managers and engineers were conducted to collect more specific evidence about MID and MIP relationships. In Automaker A, the general manager of Platform and Systems Engineering Department, the Project Engineering Department director, and an engineer from the Project Engineering Department were interviewed. In Automaker B, the R&D manager answered the questionnaire and the general manager of the Product Development Department was interviewed. Each interview lasted around one and a half hours and data was registered through paper notes (in both companies) and tape recording (only in Automaker B).

The data were transcribed right after finishing the interviews, in order to avoid losing important information and insights that occurred during the conversations (Voss, 2009). Unclear questions and answers that emerged during data collection were sent by e-mail to the interviewed persons. This allowed us to clarify specific issues and gather extra insights. Table 8.2 provides an overview of the sources and information gathered in both automakers.

Table 8.2 – Sources of evidence overview and information gathered in Automakers A and B

Source	Number		Objective	Information gathered
	Automaker A	Automaker B		
Questionnaire answered by managers	2	1	Collect preliminary data regarding modularity application	General data about application of modularity in automotive companies
Interviews with managers & product platform engineers	3	2	Explore the main aspects regarding modularity and MID and MIP relationships	Decisions criteria taken into account when applying modularity and also trying to establish MID and MIP relationships
Additional questions sent by e-mail and telephone	2	1	Collect complementary data about product development characteristics and application of modularity in cases related to the company	Additional primary empirical evidence regarding modularity in the company, to fulfill data gathered during the interviews
Specific websites	2	2		General data about product architecture and manufacturing processes, to a better understanding of modularity's general objectives and perspectives

8.3.2 Data analysis

The main objectives and conceptual elements involved in MID and MIP relationship were gathered through literature analysis about the application of modularity in the automotive industry. Data analysis process was iterative as the interviews and the questionnaires were double-checked, in order to revisit information and see if data and analysis were sound. The study followed a combined approach based on Bardin (1977) and Miles and Huberman (1994)'s guidelines and recommendations:

- Data preparation and organization: data collected from the interviews through paper notes were electronically written and organized right after conducting the interviews. Data collected from the questionnaire with managers were organized together with the field notes from the interviews. Data from both sources of evidence were aligned to enhance further analysis (BARDIN, 1977), and then organized into four groups (modularity application objectives, the impact of MID in production, MIP and manufacturing limitations to MID and common practices to MID and MIP), following the variables definition previously mentioned. This provided a systematic data organization that facilitated further researchers' coding and data reduction;
- Coding and data reduction: After organizing data into the groups of variables aforementioned, coding was used in each group to allow a systematic and precise description of the outcomes originating from the field study. Data regarding conceptual elements (showed in Figure 1) involved in the application of modularity and MID and MIP relationship trajectories were reduced and coded. Coding was also important to organize data and establish patterns for further data triangulation (YIN, 2014);
- Categorization and identification of interrelations: this step helped to identify the relations between the conceptual elements found during the study. Additionally, a map was built in order to illustrate the patterns and the relationships between the concepts (MILES; HUBERMAN, 1994). Semantics criterion was used to establish the interrelations between conceptual elements from literature and the empirical

evidence. This step helped data reduction and simplification of the whole analysis (BARDIN, 1977). Before starting the inference, data collected afterward (e.g. questions sent by e-mail) were gathered and analyzed together with data from the questionnaire and interviews in order to get additional insights;

– Data inference: this was an iterative process. Interviews, questionnaires, and field notes were revisited to build the results and analysis. MID and MIP relationship were analyzed under the conceptual elements perspective using the hypothetical-deductive method (NUNES; BENNETT, 2008). Through the interviews and questionnaire, the study identified the conceptual elements that emerged from the field (e.g. commonality, co-design with suppliers, and product platform). Then, it was established how they connect MID and MIP in the investigated companies, comparing those results with the conceptual model built through literature. This enabled the analysis of MID and MIP relationship and the building of the framework adopted by each automaker.

8.4 FINDINGS AND DISCUSSION – MODULARITY IN DESIGN (MID) AND MODULARITY IN PRODUCTION (MIP) RELATIONSHIPS

This section describes the findings on the relationships between MID and MIP in product design and production at both automakers.

8.4.1 Automaker A

Automaker A applies explicitly MID and MIP. One of the managers argues that MIP is a consequence of MID, i.e. the trajectory of the relationship is MID enabling MIP. A company's engineering manager points out that the importance of that relationship becomes clear when seeing their 'product-process conception system'. The main motivation for the predominant trajectory from MID to MIP is that design modifications incur higher costs than production modifications, supporting the findings from recent literature (e.g. ANTONELLO et al., 2015).

Yet, in the assembler perspective, the relationship between MID and MIP start when defining product characteristics, which cannot be made in a restrictive manner to one or two types of vehicles manufactured by the company. Automaker A's engineering manager states that their product design 'calls' for 'how to do' and 'what is needed' to enable the building of the best final product possible. The modular product architecture decisions give the guidelines to improve and adapt manufacturing lines. In this sense, it seems that product structure affects manufacturing arrangement and capabilities (DATTA; ROY, 2010), leading to changes in production processes (JACOBS et al., 2011).

Functionality and interdependence between modules are influential in shaping the relationship between MID and MIP. Functionality decisions are explored during the MID phase. Through those decisions, Automaker A is able to define the modules' interdependencies. Then, after establishing all functions and interdependencies, it builds the modules and the components that will be common to a certain variety of vehicles. The establishment of functionalities and their respective interdependencies enables to build standardized and common modules and interfaces, which permit decisions about what and how many modules will be shared among Automaker A's product platform. The platform and systems manager also argues that with MID enabling MIP, it allows further reduction in vehicle assembly lead-time, since the modular product architecture demands changes in production capabilities in order to assemble feasibly the designed vehicles.

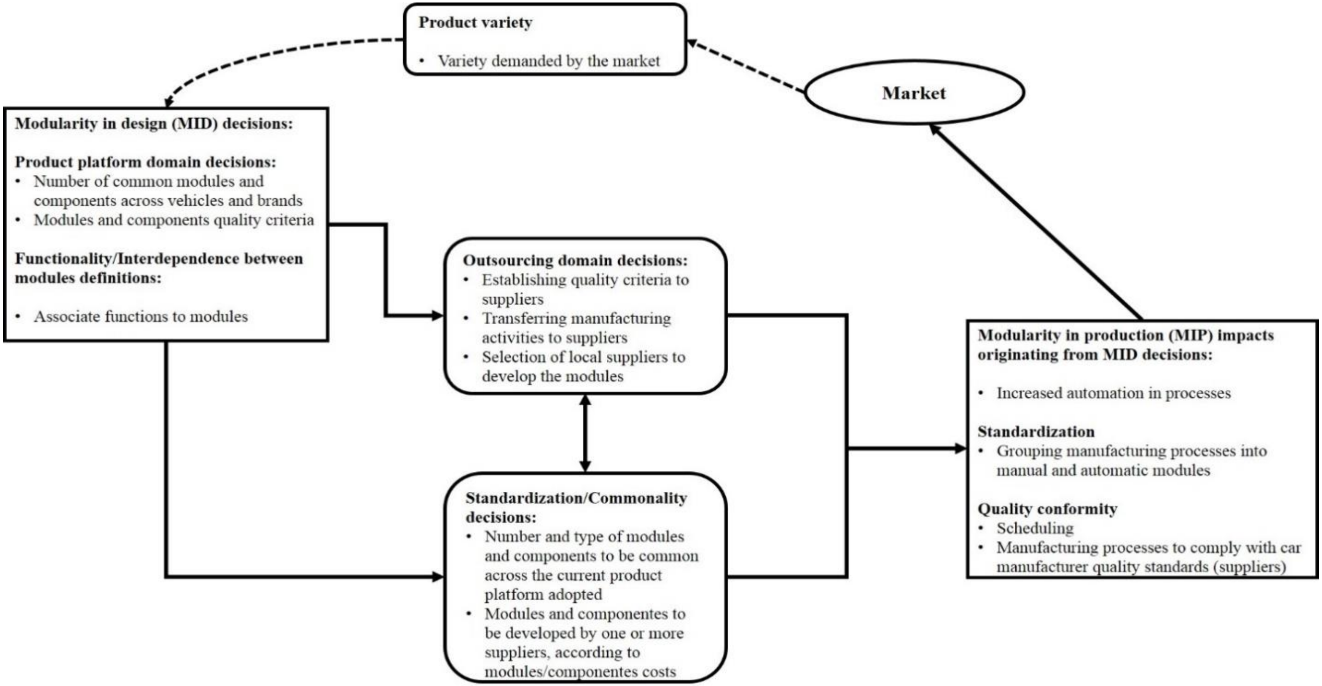
Nevertheless, despite functionalities and modules' interdependence decisions, in fact, few changes occurred with regard to changes in the manufacturing processes. The key modifications identified in Automaker A were: (i) increased automation in processes; (ii) production division into manual and automated process' modules and; (iii) avoid isolated operators over the production lines. Thereby, changes in the manufacturing processes were limited. They were incremental due to the company's available investment level. Essentially, investments were focused on raising its productive capabilities, replacing equipment and modifying technology. In this sense, the car manufacturer has not changed their manufacturing processes radically. In addition, it was possible to observe some conceptual differences about modularity between design engineers and engineers working in the manufacturing process planning. Product engineers understand modules as "a group of components physically close to each other" while manufacturing engineers see modules as "the separation of the production arrangements in terms of manual or automatic labor".

Other conceptual elements that suffered few changes involve the automakers and suppliers relationship perspective. In terms of outsourcing and co-design with suppliers, Automaker A has not faced substantial changes. The module design was an activity transferred to suppliers, but still under automaker's quality requirement. Suppliers build the whole module design and become experts on this subject, while the car manufacturer analyzes if the module would perform adequately in the whole product architecture. The automaker still has the control of the whole product design and development process.

In product variety decisions, the company analyzes market demands before building all variants needed according to customers' requests. That is, product variety is not a conceptual element intrinsically connected to modularity. The market demands more or less variety, so it is possible to take this information into account later.

Generally, although there are relationships between MID and MIP in Automaker A, they are still limited in terms of the impact of modular architecture decisions on the manufacturing processes. Since there is an established manufacturing arrangement, the company has not faced radical modifications in its production processes. Figure 8.2 shows a framework built for Automaker A. It seems that MIP is conditioned by what is done during MID decisions in the plant.

Figure 8.2 – Conceptual elements involved in Automaker A modularity decisions. Dotted lines: connections between market, product variety demands and MID decisions. Solid lines: direct connections between modularity's conceptual elements in Automaker A



8.4.2 Automaker B

Automaker B does not explicitly apply MID and MIP relationship, as argued by the R&D manager. However, data analysis showed that despite this fact, this company performs modularity decisions in product design phases that affect modularity in terms of production aspects and characteristics that contributes to some modular design definitions.

Automaker B applied modularity with three main goals: reduce costs (similarly to Automaker A), enhance its production flexibility, and restructure its local engineering team, which was limited due to previous organizational issues that occurred due to the fragmentation of the group of companies installed earlier in the country, which the company was part of. The modular product design is mostly decided by automaker the engineering department in three subsystem levels.

Initially, the product platform is organized into seven blocks, which involve fifteen modules that build up the vehicles. Those blocks compose the so-called ‘systems’, understood as the ‘modules’ according to this car manufacturer. In its development process, the automaker decides and organizes modules functionalities and interdependence among modules prior to the manufacturing and assembly basic requisites and criteria. At this stage, the relationship between MID and MIP does not exist, since the primary purpose is the alignment and compatibility among platform modules.

MID and MIP relationships are explored through the outsourcing and co-design with suppliers concepts, and the relationship trajectory is from MID to MIP through the selection of first-tier suppliers, with some features leading from MIP to MID. According to their competence, suppliers decide the components that will build the module or even propose some quality requirements and building criteria, enabling and increasing suppliers’ autonomy. The suppliers become responsible for building their respective modules since Automaker B transfers the modules’ manufacturing processes to them. In the MIP perspective, the plant’s modular concept guided some assembly specifications and pre-assembly sequencing, as well as manufacturing layout and some suppliers’ contract terms.

Then, through co-design and outsourcing, later decisions concerning the modular architecture turns the modules assembly more autonomous and independent (JACOBS et al., 2011). Each supplier is responsible for the construction of their respective modules and needs to adapt their processes following certain requirements that are defined by the car manufacturer. Additionally, Automaker B increased flexibility in production with these changes.

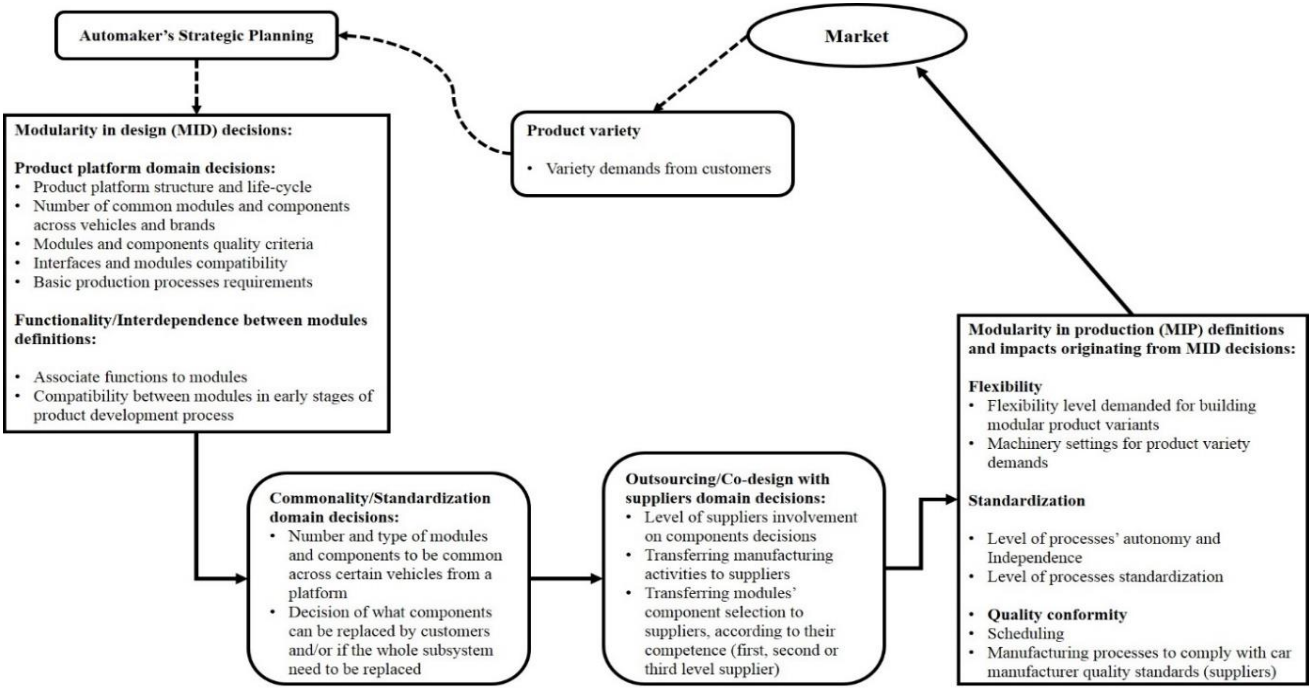
In terms of modular product design, Automaker B defines commonality and standardization concepts in terms of deciding and selecting which components and modules will be shared to a particular variety of vehicles and brands derived from the product platform. The car manufacturer applies these concepts aiming at greater component sharing and thus lower individual costs when purchasing those components. It is a decision made during the design phase. Commonality and standardization concepts are connected to the suppliers' related concepts (outsourcing and co-design). Automaker B explores the concepts by negotiating modules and components with exclusive suppliers. The automaker considers global suppliers to increase modules and components commonality and standardization since it generates more economies of scale and contributes to more standardized production processes as well as reduce changes because of less product design modifications. In addition, during modular design, the company focused on common productive processes to build various modular variants through a conceptual development in terms of product life cycle, reducing complexity and costs.

However, such decisions might bring some drawbacks. Since certain modules and components are under the responsibility of single suppliers, quality problems and/or commercial issues might generate considerable technical and organizational issues, affecting negatively a higher volume of products, with a lower possibility of overcoming the problems due to suppliers' exclusivity.

The relationship between design and production modularity may be important at the strategic level. Automaker B can prevent the loss of past investments or minimize these losses by planning modular product design with a longer life cycle. Thus, new products introduced to the market can be manufactured with a more standardized production process and requires fewer changes, since this will also be thought in advance in order to meet the current modular design variations and those that will be developed further. For Automaker B, there were difficulties in that direction since the planned product platform has changed with the development of new vehicles, which caused an impact on production in terms of increased investment for more production flexibility and interdependence.

In this sense, decisions about the product variety range are set based on the market and are handled in the company's strategic planning. However, this can serve as an input for developing modules that may attend to more vehicle variants. Figure 8.3 depicts the MID and MIP relationship applied in Automaker B.

Figure 8.3 – MID and MIP conceptual model based on Automaker B data analysis. Dotted lines: connections between market, product variety demands and strategic planning. Solid lines: direct connections between modularity's conceptual elements in Automaker B



8.5 ANALYSIS OF THE INVESTIGATED AUTOMAKERS ON MID AND MIP RELATIONSHIPS

After the analysis of the two automakers, one can observe that the identified conceptual elements demonstrate that there is a relationship between MID and MIP, and that accordingly to each company's decisions, it is possible to obtain different benefits and drawbacks. Hence, new insights on MID and MIP relationship emerged, summarized in Table 8.3.

Table 8.3 – Summary of MID and MIP implications in the investigated car manufacturers

	Automaker A	Automaker B
Objectives when applying modularity	– Reduce costs – Reduce time to market	– Reduce costs – Enhance production flexibility – Restructure the local engineering capabilities
Outsourcing/ Co-design	– Automaker decides the suppliers and the whole module and component selection – Process quality criteria under automaker's decision – Prioritization of local suppliers, to reduce costs. Greater supply chain to manage	– First-tier suppliers have autonomy to build their manufacturing processes as well as select some of the module components, according to their competence – Focus on global suppliers, to enhance economies of scale. Reduced supply chain to manage
Standardization/ Commonality	– Extensive commonality to comply with many vehicles as possible, to reduce manufacturing settings to build the modules	– Negotiation with global suppliers increased commonality among various vehicles in the same platform – More common machinery settings to build various modules/components
Functionality/ Interdependence between modules	– Functions associated to modules, which were associated and distributed among suppliers	– Functions associated to modules – Compatibility analysis between modules before prototypes

(continued...)

Table 8.3 (continued) – Summary of MID and MIP implications in the investigated car manufacturers

Main modular product design implications	– Increased commonality through more generic modules and components among various vehicle models helped to reduce design and production costs	– Better compatibility process among modules, reducing inconsistencies – More alignment between modular platform architecture and manufacturing processes through quality tools (e.g. FMEA)
Main modular production implications	– Separating production into manual labor modules and automated labor modules – Future changes in product platform will affect manufacturing processes, but limitedly	– Outsourcing assembly activities to suppliers allowed more autonomy in production processes – Future changes in product platform might affect considerably the manufacturing processes
Emerging contingencies	– Decision of selecting more local or global suppliers – Level of alignment between modularity decisions and strategic planning	

Both automakers seem to establish relationship between MID and MIP, i.e. modularity affects both design and production in the two car manufacturers, which corroborates the work of Lucarelli et al. (2015), Jacobs et al. (2011), Paralikas et al. (2011), and Campagnolo and Camuffo (2010). Yet, both companies improved their product and process compatibility through MID and MIP. During the modular product design phase, Automaker A already established some production requirements and demands in order to build the product variants needed. Automaker B used the "blocks" concept, which connected the fifteen modules that compose the company's main product platform, to evaluate the consistency among modules and to establish the basic requirements for suppliers to develop and assemble the modules. Thereby, both companies seem to establish a MID to MIP trajectory, with the product structure affecting its production (LUGO-MÁRQUEZ et al., 2016; PARALIKAS et al., 2011). That is, modular design intentionally aligned product architecture and manufacturing processes (as pointed out by JACOBS et al., 2011).

Some scholars (e.g. PARALIKAS et al., 2011; JACOBS et al., 2011) argue that modular product design decisions would have profound effects on subsequent manufacturing operations. Interestingly, although Automaker A states explicitly that MID and MIP are related, the analysis shows that such relationship is limited in terms of technical and organizational effects on manufacturing processes (in MIP perspective). That is, it still prioritizes MID significantly. Thus, evidence found in Automaker A is conflicting with the aforementioned studies. Modifications in the MIP perspective were restricted to only a few adjustments and settings in the manufacturing processes. The main implications towards MIP were the increased technology and standardizing processes into manual and automatic production modules, besides minimizing isolated operators in each workstation. Such changes were concentrated on standardized production and independent processes (as supported by SANCHEZ, 2013; JACOBS et al., 2011; FINE et al., 2005; SAKO, 2003).

Deep outcomes in MIP because of MID are not always the case, especially when there are current and established manufacturing processes that cannot be changed radically due to a limited level of investments as well as few product platform modifications. In this context, changes regarding modularity occur in different trajectories, being results of previous and current automotive industry configuration, product features, and rate of technological and organizational changes (FRIGANT; TALBOT, 2005). Therefore, this paper supports that the company has not obtained all expected benefits from modularity (as argued by ZIRPOLI; BECKER, 2011b).

Automaker B faced a more radical reorganization in their production systems than Automaker A, which is the reason that MIP features are more manifested in Automaker B than in Automaker A. Indeed, a severe internal reorganization, as well as a better coordination with suppliers, is needed to ease the shift to new modular solutions in automotive companies (LUCARELLI et al., 2015), which apparently occurred in Automaker B. In this sense, Automaker A seems more limited in terms of MID and MIP relationship than Automaker B.

In terms of MID activities and decisions, product architecture decisions are based on the product functions in Automaker A. This is a reflex of the MID prioritization in this car manufacturer. This indicates that it focuses on functionalities' definitions (RO et al., 2007; MIKKOLA, 2006) and standardized and interdependent modules (ZIRPOLI; BECKER, 2011b; JACOBS et al., 2007; PERSSON; AHLSTRÖM, 2006) in order to share them among various vehicle brands. That is, Automaker A uses standard and well-defined interfaces as coordination strategies for building cars and their manufacturing processes (as previously mentioned by CABIGIOSU et al., 2013).

Despite the fact that Automaker B does not explicitly state a relationship between MID and MIP, it is suggestive that the aforementioned car manufacturer have MID and MIP relationship in its product and manufacturing decisions. Additionally, Automaker B seems to have a higher maturity level regarding relationships between MID and MIP than Automaker A. Through an intense relationship with its suppliers (as already pointed out by ZIRPOLI; BECKER, 2011b; CAMPAGNOLO; CAMUFFO, 2009), Automaker B enabled more autonomy and independence regarding suppliers' production processes decisions. Those two characteristics (process' autonomy and independence) are related to the MIP concept (e.g. see SANCHEZ, 2013; JACOBS et al., 2011) and were identified in Automaker B, but in a more robust way than in Automaker A.

Another important distinction practice between the two automakers involve the relationships with their respective suppliers. Both car manufacturers show MID and MIP relationships features in this perspective. While Automaker A has more local and various suppliers in its supply chain, Automaker B restricted its organizational management, since it has less, however, global suppliers to manage. Both organizational structures have their embedded benefits and limitations.

Automaker A has more suppliers for similar components, as negotiates according to the best price of each local suppliers. The benefits from negotiating locally are the greater flexibility for changes when facing quality issues, since it permits to alter suppliers rapidly (if necessary), besides enabling the development of local suppliers because of decentralized decisions (IBUSUKI et al., 2012). In addition, Automaker A has more flexibility to change their suppliers and to manage quality problems when inconsistencies occur in MID and MIP activities. On the other hand, there are higher costs involved in managing a greater and more complex supply chain, as well as major adjustments needed in the production processes. It also has more complexity to manage quality conformity and suppliers activities, since Automaker A centralizes most of its product requirements.

Automaker B has more limitations to manage product and process issues when they arise, since its supply chain involves global suppliers, being harder to change them quickly due to the contracts established with those suppliers (first-tier). However, they have more economies of scale due to global provision of modules and components, being able to reduce costs and establish a medium/long range contract to attend various vehicles and brands from its current and future product platforms. In this sense, the alliance between automakers and suppliers has a considerable impact to modularity decisions, leading to implications for company’s strategy and innovation (BOUNCKEN et al., 2015).

Such context suggests a contingent factor: the decision between global and local suppliers. According to the module and/or component and to its business model, the automaker decides for a local or global component. Companies usually decide to global suppliers in order to enhance economies of scale. The negotiation with first-tier suppliers become facilitated because the modular product platform foresees various vehicle models, in short, medium and long term. Thus, global suppliers would offer modules and components for all of these variants. However, when quality and conformity issues occur, serious problems in the relationship between the automaker and suppliers may emerge, since such problems can be very costly for both the car manufacturer and the supplier. Then, working with local suppliers might be beneficial in this sense, as identified by Ibusuki et al. (2012), however, more complex for the automaker to manage the whole supply chain.

Regarding product variety, the findings of this study suggest complementary evidence. Although some studies highlight product variety as a modularity-supported concept (e.g. ZEPPINI; VAN DER BERGH, 2013; LIU et al., 2010), analysis of the two car manufacturers suggests that product variety is defined by the market, not by modularity decisions. In Automaker A, variety demands may be incorporated in modular design decisions, but after a market analysis. Similarly, Automaker B considers the market demands before analyzing their level of product variety. Then, the car manufacturer uses those demands in the modular product development. Therefore, both companies seem to consider product variety in their strategic decisions, before insert variety demands in MID and MIP decisions.

Accordingly, analysis raised another issue: the influence between modularity and company’s strategy. Apparently, Automaker B has more clarity than Automaker A in this particular topic, and this is slightly related to their modularity’s objectives, since Automaker A focused on solving technical aspects and reducing time to market, while Automaker B used modularity to enhance their local engineering team as well as increase strategic integration, connecting modularity to market, technology and business model. Thus, Automaker B seems to understand the decision about current and future generation architectures as an essential part of the company’s strategic process (SANCHEZ, 2013).

Thus, Automaker B seems to understand with greater maturity the decision about current and future generation architectures as an essential part of the company’s strategic process (SANCHEZ, 2013). This facilitated the product platform development in terms of reusing platforms and modules as well as handling modularity approach (PASCHE; SKÖLD, 2012; MAHMOUD-JOUINI; LENFLE, 2010). Additionally, Automaker B aims at a long lifecycle platform, where the vehicles developed on the platform evolve. In this sense, coordination between organizational units and product platform development is a complex action for automakers (PERSSON; AHLSTRÖM, 2013).

In this context, this paper suggests another contingent factor: the relationship and/or alignment between modularity definitions and the company's strategy. Such decisions may be centralized (defined by the automaker's headquarters) or decentralized, enabling more autonomy to the established local centers define some variations resulting from the modular platform (AMATUCCI; MARIOTTO, 2012; IBUSUKI et al., 2012). As the final project and its manufacturing processes are established, changes in the manufacturing processes can occur in great or less extent in the future. Such modifications in design and production might be related to each company’s modularity objectives (SANCHEZ, 2013). Updates and extensions preview regarding the modular product platform requires a number of changes in the supply chain. The whole chain might become modular in order to comply with the variations and modules planned in product platform design effectively.

8.6 CONCLUDING REMARKS OF THIS CHAPTER

This paper has investigated the relationships between MID and MIP and their implications in two Brazilian car manufacturers. The analysis indicates that decisions regarding MID have technical and organizational impacts on production settings towards MIP, through the conceptual elements identified in both car manufacturers. Those conceptual elements show the main features involved in MID and MIP relationships, such as commonality, standardization (of components and interfaces), co-design with suppliers, functionality, product platform, outsourcing and interdependence between modules.

This study also demonstrates that MID and MIP relationships may contribute to reducing incompatibilities and increase synchrony between modular design and production. Both car manufacturers investigated seem to align modular design definitions with their production capabilities, even though with limited adjustments towards MIP. Thus, they can prevent themselves from planning MID without taking into account further implications in manufacturing processes (and vice-versa), which could bring some serious inconsistencies between product design and manufacturing requirements and production dynamics, capabilities and investments needed.

The paper has, however, some limitations, being the first with regard to data collection. Most consulted automakers refused to participate arguing that MID and MIP relationships are strategic information and not suited for academic purposes, and consequently, the investigated companies did not offer a greater variety of sources of evidence. That also resulted in a field study involved two automakers. Thus, it is not possible to provide wider external validity. Furthermore, the paper offers some contingent factors that might be influential in MID and MIP relationship but argues them briefly. Therefore, it requires further in-depth investigation.

As opportunities for further research, some promising topics raised. Deepen and focus on the main contingent factors such as modularity and strategic planning and the decision between local or global suppliers in MID and MIP relationships context is a raising opportunity for further studies. Another promising topic is to analyze and compare MID and MIP relationships in alternative drivetrain vehicles. Those relationships might affect decisions regarding important components and systems such as the battery, electric drivetrain system and high-voltage supply, three of the most added-value modules in alternative powertrain concepts. Research about modularity adoption in this increasing market, which is the conception of future alternative vehicles, may bring important contributions to the field.

9 DISCUSSION AND MAIN THESIS CONTRIBUTIONS

This chapter presents a general discussion of the findings described in the previous chapters and points out the main contributions of this research from both theoretical and managerial perspectives.

9.1 SUMMARY OF THE ARTICLES' CONTRIBUTIONS

This section presents an analytical summary of the contributions made by each article that built up this thesis. Table 9.1 summarizes those main contributions.

Table 9.1 – Summary of the main contributions of the articles

Chapter (article)	Main contribution
Chapter 3 (Article 1)	Identification of modularity as a relevant strategy to develop automotive projects, as well as an analysis focusing on each of the investigated vehicles
Chapter 4 (Article 2)	Identification of different modularity typologies, concepts and their respective variations; main industrial sectors applying modularity; and the most applied modularity typologies in the automotive industry
Chapter 5 (Article 3)	Identification of MID and MIP relationships as a promising approach to be applied by automotive companies
Chapter 6 (Article 4)	Development of a preliminary conceptual framework detailing MID and MIP theoretical relationships in the automotive industry
Chapter 7 (Article 5)	Development of the final conceptual framework considering MID and MIP relationships in the automotive industry; identifying the main conceptual elements of each MID-MIP trajectory
Chapter 8 (Article 6)	Empirical verification of the MID-MIP conceptual framework; technical and organizational impacts analysis of the MID and MIP relationships; practical evidence that MID enables/guides MIP (corroborating the literature analysis)

Article 1/Chapter 3 highlighted some important approaches in the product development process in the Brazilian automotive industry, such as local R&D centers, the launching of a new segment, locally commanded product design and modularity. This chapter points out the main implications that modularity brought to the investigated vehicles (Renault Sandero, VW Fox, Ford EcoSport, Fiat New Uno and GM Meriva), pointing out that MID and MIP appeared as the main typologies applied, with some indications of the connections between them.

Chapter 4/Article 2 pointed out and summarized the broad interpretations of modularity concepts, according to each approach (MID, MIP, MIU, organizational modularity, and service modularity). It contributes by evidencing that modularity typologies have a tight theoretical connection among themselves and stating that MID guides the application of other modularity approaches. These findings suggest that MID is the most developed modularity approach, theoretically.

Article 3/Chapter 5 focused on MID application in the automotive industry, by analyzing the pertinent literature on the topic. This study identified that MID is the most exposed typology in modularity literature. The chapter also recommends focusing on most added-value modules, to improve product quality and manufacturing capabilities. Such results may support, when developing MID, the identification of the most added-value modules and a focus on their development in order to obtain higher benefits from modularity strategy.

Chapters 6 and 7 (Articles 4 and 5, respectively) presented the development of the conceptual framework. Chapter 6/Article 4 focused on the identification of the conceptual elements involved in MID and MIP relationships, this being Chapter 6's main contribution. Subsequently, Chapter 7/Article 5 expanded this contribution by specifying how each of those constructs affects MID-MIP relationships as well as the trajectories of the above-mentioned relations.

Finally, Chapter 8/Article 6 offered an empirical contribution by demonstrating the applicability of the conceptual framework through a field study, highlighting the main technical and organizational implications identified in the two investigated automakers regarding MID-MIP relationships.

The next section presents the main contributions of the thesis as a whole, pointing out the conceptual framework development, its managerial implications, and the lessons learned from the case studies in terms of modularity objectives and possibilities through the developed framework in this thesis.

9.2 CONCEPTUAL FRAMEWORK: THEORETICAL CONTRIBUTIONS AND MANAGERIAL IMPLICATIONS

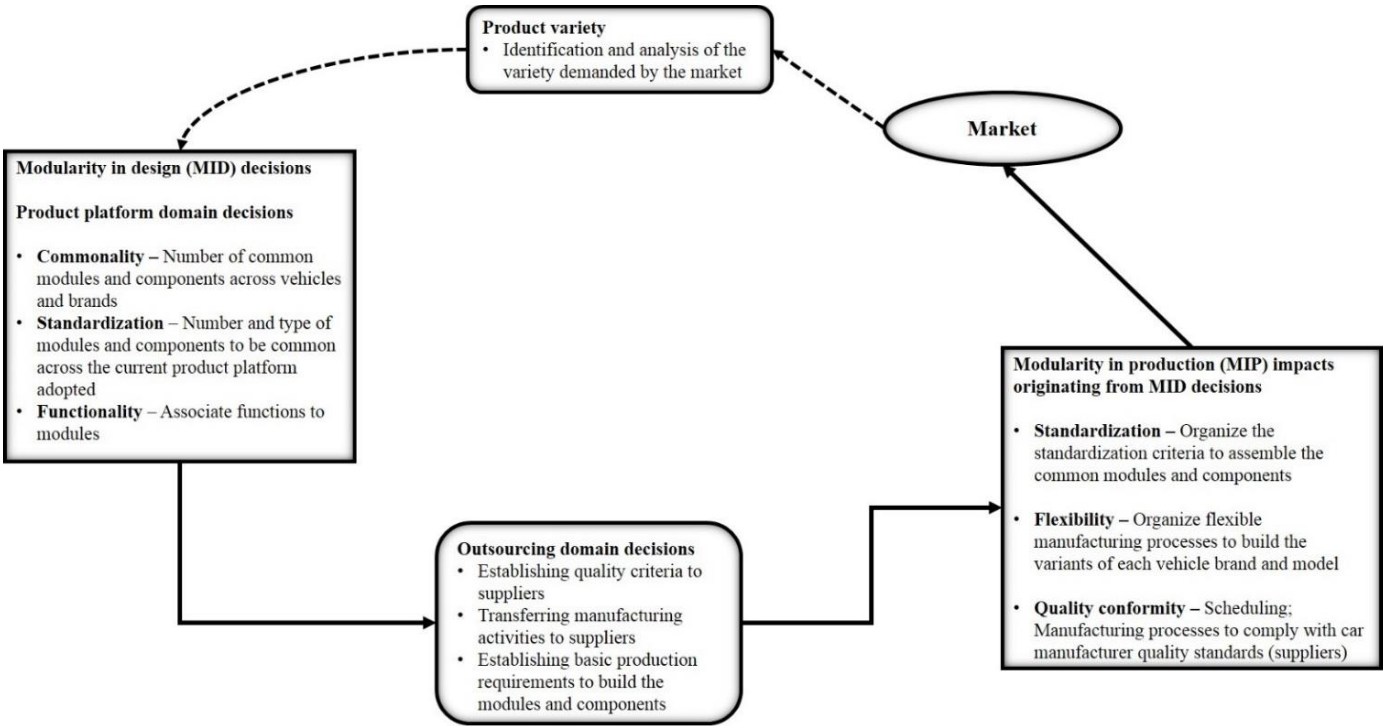
First, the thesis verified that the developed framework has as its main contribution a systematic presentation and demonstration of the primary constructs involved in modularity application in automotive companies. Those conceptual elements that build the conceptual framework have previously been loosely identified in the literature and are often investigated in isolation. Additionally, those elements had not been considered integrated. Hence, this thesis contributes to the identification and analysis of the main constructs that underpin MID and MIP relationships, making it possible to improve modular product architecture and modular production. Additionally, the synthesized identification and organization of these concepts may be valuable to help scholars examine how the main conceptual elements affect modularity decisions in other companies that adopt modular strategies in their products and processes.

Furthermore, the conceptual framework developed in this thesis has the flexibility to be applied according to automakers' current demands, in terms of both new product modularization and product redesign (under the modular approach). Thus, according to the company's objectives regarding modularity application, the framework can be adjusted to be implemented, meeting those needs. The framework integrates product design and its manufacturing processes under the modular strategy (as already pointed out by PIRAN et al., 2015). It also contributes to understanding how MID may enable MIP (and vice versa) to achieve a better synchronization between product architecture and manufacturing processes from the modular perspective.

Accordingly, Chapter 9 presents two examples of possible objectives and their respective frameworks for modularity application. Those two examples were based on the objectives pointed out by the investigated automakers in this thesis field study. For instance: if the company's objective is to reduce manufacturing and design costs, the initial focus should be the conceptual elements aligned with such a goal. Thus, concepts such as commonality, standardization, and functionality may guide decisions regarding the product platform development. The more extensive use of common modules within a given product platform will increase economies of scale through greater sharing of modules. Then, the three above-mentioned conceptual elements (commonality, standardization, and functionality) may guide modularity decisions, with

MID enabling MIP. Figure 9.1 illustrates an alternative for applying modularity in a costs-reduction scenario.

Figure 9.1 – Conceptual framework developed to focus on costs reduction (based on Automaker A's objectives)

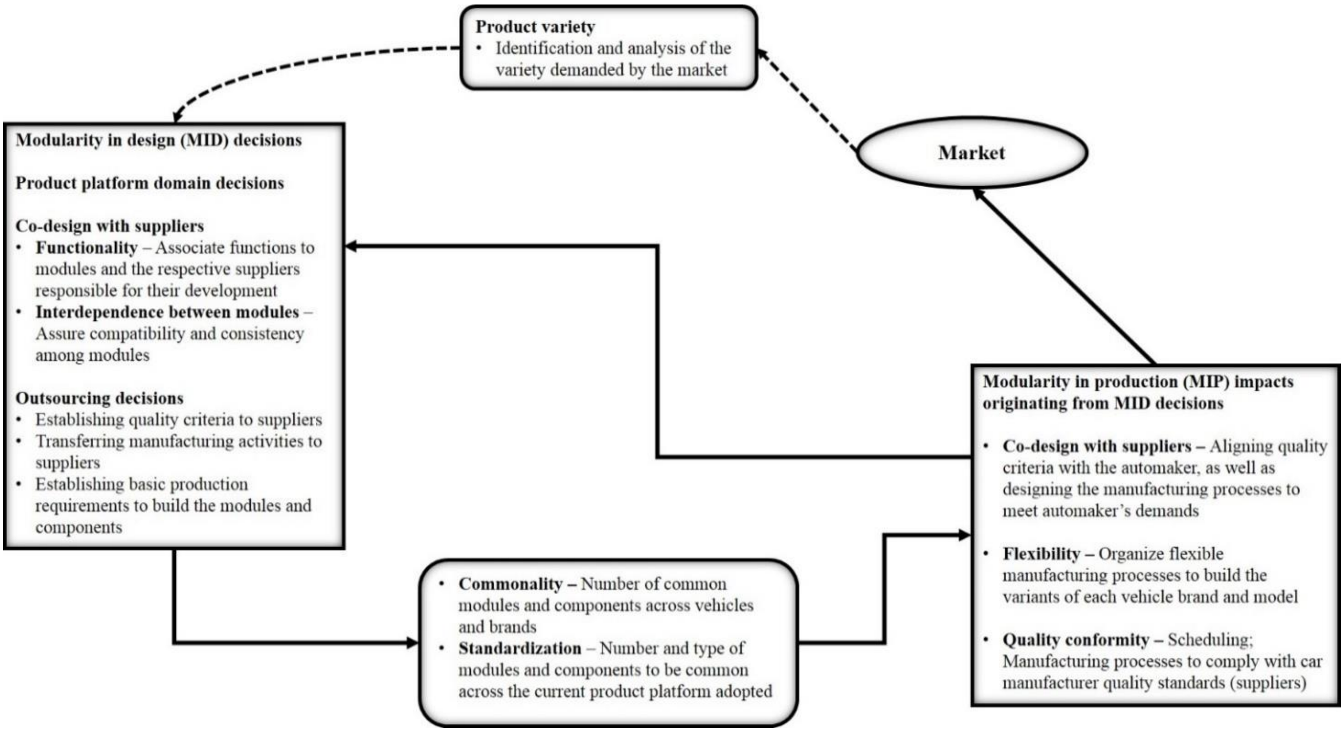


However, there may be other objectives when applying modularity. Another possibility, which emerged in one of the investigated companies (Automaker B), is the restructuring of the company's local engineering and manufacturing plant, specifically in terms of new product development. Along with that, new suppliers were hired to work together with the automaker, under the modular strategy.

From that objective, it becomes clear that both modularity perspectives (MID and MIP) were needed. Such a context favored both MID and MIP implementation by involving suppliers from the beginning of the product development process, outsourcing engineering and manufacturing activities. This scenario enabled an extensive application of MIP through more autonomous and independent processes, using the suppliers' capabilities to build the industrial plant, which allowed cost reduction and increased flexibility in production. Those benefits might help in designing the new product platform modules. Concepts such as outsourcing and co-design with suppliers guided modularity decisions.

Additionally, MIP may affect the modular product platform quality and development (VICKERY et al., 2016). Furthermore, concepts related to MID and MIP such as co-design with suppliers, standardization and product platform, were explored significantly. Such a scenario demonstrates that MID application, through engineering decisions along with first-tier suppliers, demanded standardization both in the modules and in the manufacturing processes, as well as in the requirements defined previously. Figure 9.2 presents a proposal based on the idea of restructuring engineering and manufacturing activities (with increased suppliers' participation).

Figure 9.2 – Conceptual framework developed to focus on costs reduction (based on Automaker B's objectives)



The conceptual framework developed in this thesis demonstrates that, besides systematizing the main primary constructs that guide MID and MIP decisions, it also might have the flexibility to develop modular strategies suitable to the objectives and needs that each automaker may have. The identification of those goals occurred in the field study, which illustrated some circumstances involving MID and MIP relation as well as the trajectories of that relationship. Thus, the framework has the potential to inhibit technical and organizational inconsistencies between the design and manufacturing processes (similar to what was suggested previously by PANDREMENOS et al., 2009; PARALIKAS et al., 2011). Accordingly, this thesis considers the possibility of various contingencies when adopting MID and MIP. It is noteworthy that each unit of analysis has particular characteristics that affect modularity decisions, such as the existence of an established manufacturing arrangement or whether a new production plant was designed to support MID-MIP relationships. The field study highlights that automakers' decisions regarding modularity and its concepts may yield different benefits and drawbacks.

Furthermore, as the identification of contingent factors was not an objective of this thesis, it is noteworthy to mention that some contingencies (e.g. the decision to hire local or global suppliers; the relationships between strategic planning and modularity objectives) were identified, but not deeply investigated. Then, although the thesis suggests that the MID-MIP conceptual framework considers some contingencies involved in modularity application, such a demonstration still needs further research, especially in terms of analyzing the main contingent factors influencing modularity application in the automotive industry. The next chapter points out the conclusions, limitations and further research opportunities identified in this research.

10 CONCLUSIONS

This thesis aimed to investigate the organizational and technical impacts of the relationships between MID and MIP, analyzing the modularity activities and decisions of car manufacturers that had applied the concept. In order to accomplish this overarching objective, the following specific objectives were developed: (i) identify and analyze the common and particular characteristics of the most relevant automotive vehicle projects and automakers regarding the application of modularity; (ii) identify the main conceptual elements associated with modularity and examine how they establish MID-MIP relationships; and (iii) verify the relationships between MID and MIP and analyze how they can generate benefits and/or limitations in terms of organizational and technical decisions in car manufacturers. This chapter presents the main concluding remarks, the limitations, and the further research opportunities that emerged during the research.

10.1 CONCLUDING REMARKS

The initial phase of the literature review revealed that modularity advantages are still more exposed than challenges. The empirical investigation corroborates those theoretical findings, pointing out that modularity's benefits are more externalized than its drawbacks, and that OEMs obtain more of those benefits than suppliers. Additionally, though the literature points to an increasing relationship with suppliers, the field study shows that automakers still play a prominent role in addressing both MID and MIP. That is, the case studies conducted show that suppliers have less autonomy than the literature suggests. Although engineering suppliers have increased both their expertise in specific modules and their autonomy to develop them, the activities and decisions are still mostly controlled by the OEMs. Moreover, unlike the current modularity literature (which usually suggests that modularity enables decisions on product variety), the field study demonstrates that product variety is developed prior to modular definitions. Such evidence suggest that modularity still brings more impact to the product design than to the production processes, as the pertinent literature on the subject and the empirical evidence suggested.

The second phase of the literature analysis (i.e. the conceptual framework building), the examined automotive examples, and case studies all expose that some companies fail to obtain the maximum benefits of modularity because they plan MID without considering any further implications for manufacturing processes. Hence, the thesis argues that analyzing modularity concepts and objectives to establish MID-MIP relationships may be important to increase the advantages of modularity. The investigated car manufacturers aligned their modular design definitions with their production capabilities, despite having limited MIP-oriented adjustments. They were able to plan MID by considering further implications in manufacturing processes (and vice-versa). Therefore, this thesis affirms that the relationships between MID and MIP indeed improve compatibility among the modules and between the product platform design and manufacturing arrangements, reducing the risk of inconsistencies and improving the synchronization between module design and modular production.

The case studies conducted in this study reinforced the applicability of the conceptual framework, which may be useful for redesigning functions, structures, and management. The development and verification of the framework revealed that both the literature and practice highlight MID more than MIP, and that automakers conduct their main decisions during MID activities, prior to MIP definitions. MID definitions involve functionality, commonality, and interdependence between modules and product platforms. That is, such decisions will affect MIP development afterwards. Hence, the thesis demonstrates that MID normally guides MIP decisions through the aforementioned constructs. From those findings, modular design usually guides modular production definitions, because MID is more developed in both theory and practice than MIP, and also because design definitions occur more frequently prior to manufacturing definitions in terms of structure and investments needed.

Lastly, companies that are interested in developing new modular products may also consider using the framework to facilitate their product design and production requirements. Such applications may guide managers and scholars in planning modular design, taking into consideration its technical and organizational impacts on modular production-related manufacturing capabilities (or vice versa). The next section presents the thesis limitations and further research opportunities identified.

10.2 LIMITATIONS AND FURTHER RESEARCH OPPORTUNITIES

This thesis has some limitations. First, from the methodological perspective, only two case studies were carried out, which could limit external validity. However, the empirical investigation was sufficient to suggest theoretical implications and raise some managerial impacts, because the field study collected multiple sources of evidence from both companies. This enhanced internal validity and construct validity.

Additionally, the thesis identified promising opportunities. The initial stage of the literature review contributed to a broader analysis of the main subjects to be further investigated within the modularity area. An emerging research opportunity in this stage involves the fact that there is no consensus regarding a universal concept of modularity. This thesis suggests that this global concept can hardly be reached because each modularity typology has particularities that involve the focus of the application. Consequently, studies that define an ontology for modularity could be an interesting direction for further research.

Yet, the thesis also proposes that certain contingencies affect MID–MIP relationships. As mentioned in the previous chapter (Chapter 9), factors like production capabilities, selection of local and/or global suppliers, and level of decentralization in the product development process appear to influence MID-MIP relationships. Those contingencies emerged during the case studies; however, they were not deeply analyzed in terms of how they affect modularity decisions and implementation. Hence, further research should also scrutinize the contingencies involved in MID and MIP application in automotive companies.

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APPENDIX A – First page of the six papers presented in the thesis

Paper 1 – Published in Product: Management & Development, 2012.

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Towards a contribution to modularity concepts and principal domains

Leonardo de Aguiar Corrêa, Flávio Issao Kubota, Paulo Augusto Cauchick Miguel
Universidade Federal de Santa Catarina
e-mails: leco.aguiarcorrea@gmail.com; flavioissao.kubota@gmail.com; cauchick@deps.ufsc.br

Abstract: Modularity concept emerged in the 1960's within the computer industrial sector, bringing considerable competitive advantages and benefits. Since this period, modular approach has been applied in many industrial sectors, such as automotive, electronics, furniture and others. In this sense, this study examined papers regarding modularity and their applications in the industrial and organizational perspectives, towards a concept better understanding and context where it is applied. A theoretical-conceptual paper was carried out through a hypothetical-deductive method to analyze the publications. Results show similarities and discrepancies among modularity concept variations. In addition, it was perceived that automotive industry has been sorely using modularity in design, production and use. Lastly, benefits, difficulties and recommendations were identified in the modular approach adoption. Thus, it can be concluded that a difficult still remains in defining a unique and broad modularity concept, due to variants according to the modularity approach (design, production, organizational, etc.) utilized. Future studies should search for a better understanding about variations of modularity concept, trying to find what characteristics are predominant throughout all concept variants.

Keywords: modularity, modularity in design, modularity in production, modularity in use, organizational modularity.

1. Introduction

Modularity concept has been widely utilized since the beginning of the 21st Century. However, the concept emerged before, in the 1960's within computer industry, bringing competitive benefits and demonstrating significant importance in the product development process (ARNHEITER; HARREN, 2006). Besides, modularity helps designers and engineers in the development of products which have potential to comply with different markets (CARDOSO; KISTMANN, 2008). During the past years, companies are increasingly forced to optimize their resources, adapt themselves to the global market dynamics and satisfy consumers, which are getting more demanding due to a broad access to information. In this context, one of the strategies that helps to improve product and process quality is modularity, which aims to (BALDWIN; CLARK, 2004; CARNEVALLI; VARANDAS JÚNIOR; CAUCHICK MIGUEL, 2011): facilitate the management of complex products and processes through the division into simpler modules; enable parallel production activities, since modules can be manufactured simultaneously; and adapt production to future uncertainties, because the final product might be modified by adjustment of a single module or component, requiring a lower cost than redo the whole product.

As mentioned earlier, modular products are designed as a set of independent and simpler modules, which can be reused and interchanged to maximize product variety (STARR, 1965). Thus, modular products supports standardization that facilitates (re)manufacturing, helps to eliminate waste, and decreases costs. In addition, modularity is an attribute of a complex system that advocates designing structures based on reducing interdependence between modules and maximizing interdependence within them that can be mixed and matched in order to obtain new configurations without loss of functionality or performance in the system (LANGLOIS, 1992; BALDWIN; CLARK, 1997; CAMPAGNOLO; CAMUFFO, 2010). In other words, modularity has many facets starting with interchangeability of parts (STARR, 2010). According to the previous author, modularity varieties stem from different concept applications of units of interchangeability.

During the past decades, modularity attracted the attention of numerous management scholars (CAMPAGNOLO; CAMUFFO, 2010). In addition, authors have been studied the subject in several perspectives: product modularity (CARIDI; PERO; SIANESI, 2012; HUANG et al., 2012; LAU; YAM; TANG, 2011), process modularity (PARENTE; BAACK; HAHN, 2011; JACOBS et al., 2011), service modularity (GEUM; KWAK; PARK, 2012; LIN; PEKKARINEN, 2011; BASK et al., 2011) and/or production modularity (RODRIGUES; CARNEVALLI; CAUCHICK MIGUEL, 2009; DORAN et al., 2007) as well as the impact on the final products quality (LAU; YAM; TANG, 2009), critical factors in the modular product management (LAU; YAM; TANG, 2010) and competitive advantages through the modular strategy adoption (JACOBS; VICKERY; DROGE, 2007).

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Design modularity: identification of benefits and difficulties through a bibliographical analysis in the perspective of automotive assemblers and suppliers

Flávio Issao Kubota, Leila Amaral Gontijo, Paulo Augusto Cauchick Miguel
Universidade Federal de Santa Catarina
e-mails: flavioissao.kubota@gmail.com; leila@deps.ufsc.br; cauchick@deps.ufsc.br

Abstract: Modularity is a powerful concept applied in various industrial sectors. It assists designers and engineers in the development of products that have potential to comply with different markets. In this sense, this paper aims to analyze the literature on modularity focused on design modularity within the automotive industry. This sector has been increasingly applying the concept of modularity. It is a theoretical study that considered articles published in the past five years (since 2007) with regard to the issue "design modularity in the automotive industry". Publications were retrieved from peer-reviewed journals at major databases. The search identified 123 articles, from which 45 were suitable for content analysis. Results show that most recent publications cited as major benefits the customization, increased flexibility and product variety, and cost and time vehicle development reduction. The main difficulties are related to increased suppliers dependence (by vehicle assemblers) as well as innovation constraints by suppliers. Other aspects of the publications associated to the research approaches employed in the publications are also presented. Conclusively, benefits of modularity in design have been more exposed in the literature compared to the difficulties in the context of the automotive sector. It is observed that Original Equipment Manufacturers have more benefits than suppliers do, as the latter have more difficulties to adapt their organizational and productive processes towards design modularity. Finally, it is expected that the present work contributes to a broad theoretical framework concerning the benefits and difficulties of design modularity in the auto industry.

Keywords: modularity, modular design, automotive industry, literature analysis.

1. Introduction

Differentiated and innovative products have been increasingly desired and demanded by customers, who have become more discerning in their purchasing decisions. In areas where competitiveness is more intense, a creation of a differentiated product provides possibilities to the companies to be in the market.

One of the strategies that helps to improve products and processes is modularity, which aims to (BALDWIN; CLARK, 2004; CARNEVALLI; VARANDAS JÚNIOR; CAUCHICK MIGUEL, 2011): facilitate the management of complex products and processes through the division into simpler modules; enable parallel production activities, since modules can be manufactured simultaneously and; adapt production to future uncertainties, because the final product might be modified by adjustment of a single module or component, requiring a lower cost than redo the whole product (CORRÊA; KUBOTA; CAUCHICK MIGUEL, 2012). The concept of modularity is present in a variety of industries such as electronic, computing as well as the automotive sector. Those industrial sectors apply the modular strategy in their products and processes (ARNHEITER; HARREN, 2006; SALERNO et al., 2009). Moreover, it is clear that with the automotive sector growth and a consequent increase in vehicles' production and consumption in Brazil and worldwide, there has been a high increase in competition among automobile organisations.

In this context, series of decisions need to be taken into consideration to apply modularity in vehicle design, which demonstrate the complexity of this strategy (ASAN; POLAT; SERDAR, 2004). Like other strategies and methods, decisions about the design modularity degree and the choice of production processes significantly affect project development costs of cars. In this sense, this study conducts a review and a preliminary organization of the literature regarding the benefits and difficulties of design modularity in the automotive industry. One of its purposes is to offer a broad overview of this strategy for vehicle development. This work is part of a major research project on modularity, which previous results were published earlier (CAUCHICK MIGUEL, 2004, 2005; CAUCHICK

Paper 3 – Published in GERPISA Conference 2013 in Paris, France

Identification and analysis of characteristics of development of vehicles in the Brazilian automotive industry

Flávio I. Kubota and **Paulo A. Cauchick Miguel**

Federal University of Santa Catarina (UFSC), Florianópolis, SC, Brazil

Abstract: Brazilian automotive industry has been facing several and important changes in its products, processes and services since the 90's, which brought considerable improvements in the automobile supply chain. In this sense, this paper identifies and analyses the common and specific features in locally developed passenger cars that have brought competitive advantages in new product development in the Brazilian automotive industry. This work is basis for a theoretical framework regarding the main characteristics that influence carmakers' success in the country. Through a theoretical study based on various sources, it was possible to find out those common aspects such as local R&D centres, modularity strategy and tax policies as well as specific features such as product redesign or a new market segment creation. Those are the main issues that brought benefits to both OEMs and their customers.

Keywords: Brazilian automotive industry; vehicle design; new product development; R&D; modularity; Brazil.

1. Introduction

A new competition scenario in Brazil emerged from the market opening in the 1990s. Inflation reduction and a new free trade agreement among Brazil, Argentina, Uruguay and Paraguay became the national consumer market more demanding and more competitive (Sanchez *et al.*, 2012). This has occurred also due to the growing competition and the customers' search for products more suitable to their needs and expectations in many industrial sectors, among them the automotive.

Although the automotive industry is widely regarded as one of the most global sectors, it remains geographically dominated by determined regions. An overall vision of the automotive sector shows that the annual automobile production represents only 1% of the worldwide population and it is concentrated in large markets such as North America, Western Europe and Asia and Pacific. These markets account for more than 90% of international production volume and about 70% of passenger car production in recent years (Hung, 2007; Ibusuki *et al.*, 2012).

However, these traditional (or mature) markets suffer due to a natural saturation and, as a consequence; their automotive industries consider the BRIC nations (Brazil, Russia, India and China – emerging economies) as solution for survival and expansion (Hung, 2007). Subsequently, the emerging markets is accounting for more share, declining the 'Triad' region (North America, Western Europe and Japan) and only a portion of automotive production (Ibusuki *et al.*, 2012). Brazil was one of the countries that has received most automotive manufacturers plants in the world (Cardoso and Kistmann, 2008), with estimates of 13 automakers and investments around US$ 6.5 billion until 2014 (Sasaki, 2012). Since the OEM pioneers other newcomers have arrived in the country (see Table 1). This shows that since its introduction in Brazil, the automotive sector has undergone important changes concerning location and positioning of product development activities and the organisation of production processes within the context of companies working in this supply chain (Salerno *et al.*, 2009).

Paper 4 – Published in EurOMA Conference 2015 in Neuchatel, Switzerland

Analysis of the theoretical relationships between product and production modularity and their implications in the automotive industry

Flávio Issao Kubota (flavioissao.kubota@gmail.com)
Federal University of Santa Catarina (UFSC) / Copenhagen Business School (CBS)

Paulo Augusto Cauchick Miguel
Federal University of Santa Catarina (UFSC)

Juliana Hsuan
Copenhagen Business School (CBS)

Abstract

Research in modularity design and in production systems in the automotive industry is increasing, as many Western and Japanese firms are applying this concept. This study focuses the relationships between modularity in design (MID) and production (MIP). After analysing 60 papers on MID and MIP in automotive companies, it was observed that some publications suggest that relationships between MID and MIP can be two-ways, i.e. not only the former affects the latter, but the latter also affects the former. Conclusively, the relationships between MID and MIP are relevant and future studies should emphasise how they produce managerial benefits and/or drawbacks.

Keywords: Modularity in design, Modularity in production, Cause and effect relationships

1. Introduction

The automotive industry is one of the most complex industries in terms of technology and agents involved in the innovation process. In order to reduce this complexity, modularity concept emerged, and has been widely used in the automotive sector. This concept was originated in the computer industry during the 1960s, generating competitive advantage and demonstrating significant importance in product development process (Arnheiter and Harren, 2006).

Within this context, a relevant issue was raised, which is the relationships between modularity in design (MID) and modularity in production (MIP) in the context of automotive industry. MID and MIP relationships have recently begun to attract scholars' attention, as many European, Japanese and North-American automotive firms are applying this concept to analyse how product and production modularity affect efficiency and competitiveness. Additionally, emerging economies like Brazil has been conducting more added-value product development activities in the past decades, which lead to some important changes within the automotive sector (Salerno et al., 2009), particularly from the modularity perspective.

Paper 5 – Published (online) in the International Journal of Advanced Manufacturing Technology

Int J Adv Manuf Technol
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ORIGINAL ARTICLE

Theoretical analysis of the relationships between modularity in design and modularity in production

Flávio Issao Kubota[1] · **Juliana Hsuan**[2] · **Paulo Augusto Cauchick-Miguel**[3]

Received: 11 May 2016 / Accepted: 25 July 2016

Abstract This paper investigates the relationships between modularity in design (MID) and modularity in production (MIP) in the automotive industry in terms of how automotive companies obtain benefits and/or drawbacks through MID/MIP relationships. A literature analysis was conducted in order to identify the possible relationships between MID and MIP as well as the concepts behind these connections. Sixty-one papers were identified to portray relationships between modular product architecture and modular production systems. Results show a representation of MID and MIP relationships by illustrating that many automotive firms are working towards establishing a better connection between these modularity typologies. Those relationships may occur in both ways and involve various conceptual elements, which are important in guiding managers' decisions regarding applications of modularity. From the analysis, two propositions are offered for future field research. Finally, relationships between MID and MIP might be connected with modularity's maturity level in companies. This is a literature review paper; therefore, empirical evidence is needed to further support current findings. Future studies could analyze the managerial implications through causal relationships between MID and MIP. In addition, the propositions that emerged from this study may provide a foundation for conducting empirical research. As main contributions, this paper establishes the relationship trajectories between MID and MIP in a systematized way, which enables to describe the main specific conceptual elements involved in MID and MIP relationships. Additionally, it offers propositions on how these relationships may increase practical relevance and grounds for field analysis.

Keywords Modularity · Modular design · Modular production · Literature review · Automotive sector

1 Introduction

Modularity has attracted the attention of numerous management scholars, especially in products, production systems, and organizations [1], due to its potential to generate competitive advantage and its significant importance in the product development process [2]. There are two distinct perspectives/dimensions of the use of modularity: modularity in design (MID) and modularity in production (MIP). The former aims at decomposing complex products into complete functional subsystem units, which can be designed and manufactured independently; this enables construction of different products by combining subsystems, reducing complexity while integrating functionality [3, 4]. The latter is characterized by organizing production processes into standardized groups [5] that have few strong organizational ties [6], permitting resequencing and tooling with little loss in functionality due to each production module working as a fairly autonomous

✉ Flávio Issao Kubota
flavioissao.kubota@gmail.com

Juliana Hsuan
jh.om@cbs.dk

Paulo Augusto Cauchick-Miguel
paulo.cauchick@ufsc.br

1 Post-Graduate Program in Production Engineering, Federal University of Santa Catarina, Campus Universitário Trindade, Caixa Postal 476, 88040-970 Florianópolis, SC, Brazil

2 Department of Operations Management, Copenhagen Business School, Room SOL/B5.27, Frederiksberg, Denmark

3 Production and System Engineering Department, Federal University of Santa Catarina, Campus Universitário Trindade, Caixa Postal 476, 88040-970 Florianópolis, SC, Brazil

Published online: 04 August 2016

APPENDIX B – List of contributions from the doctoral research

Phase	Paper Title	Status	Year	Qualis-Capes/ Impact Factor (2015)
Literature Review – Modularity concepts, domains and theoretical-empirical research opportunities	An analysis of publications on modularity in the automotive industry in the major journals in Industrial Engineering in Brazil – **Exacta**, v. 10, n. 2, p. 223-236, 2012.	Published (In Portuguese)	2012	B5
	Towards a contribution to modularity concepts and principal domains – **Product (IGDP)**, v. 10, n. 2, p. 01-12, 2012.	Published	2012	B4
	Modularidade nos setores industriais de bens de consumo: perspectivas futuras de pesquisa por meio de uma análise da literatura. 33 Encontro Nacional de Engenharia de Produção – XXXIII ENEGEP. Salvador-BA. 2013 (In Portuguese).	Published	2013	National conference
	Literature classification and analysis on modularity: future perspectives for further research – **GEINTEC**, v. 4, n. 1, p. 604-621, 2014.	Published (In Portuguese)	2014	B3
	Benefits and Difficulties of Product Modularity: Preliminary Literature Analysis. 22 International Conference on Production Research. **Proceedings...** XXII ICPR. Foz do Iguaçu-PR. 2013.	Published	2013	International conference
	Design modularity: identification of its benefits and difficulties through a bibliographical analysis in the perspective of automotive assembler and suppliers – **Product (IGDP)**, v. 11, n. 1, p. 24-32, 2013.	Published	2013	B4

(continued…)

APPENDIX B (continued) – List of contributions from the doctoral research

Literature Review – Vehicle development in Brazilian automotive industry	Vehicle development in Brazil: identification and analysis of common and specific characteristics of passengers cars based on the literature. **Proceedings...** XIX SIMPEP. Bauru-SP. 2012 (In Portuguese).	Published	2012	National conference
	Identification and analysis of characteristics of development of vehicles in the Brazilian automotive industry. GERPISA International Colloquium. **Proceedings...** GERPISA. Paris-France. 2013.	Published	2013	International conference
	Uma visão do desenvolvimento de veículos na indústria automotiva brasileira. In: **Gestão da Produção e Operações: Bases para Competitividade**. São Paulo: Atlas. 2014 (In Portuguese).	Published	2014	Book Chapter
Theoretical-Conceptual framework – Development and empirical application	Analysis of the theoretical relationships between product and production modularity and their implications in the automotive industry. Proceedings… EurOMA. Neuchatel-Switzerland. 2015.	Published	2015	International conference
	Analysis of the Relationships between Modularity in Design and Modularity in Production. International Journal of Advanced Manufacturing Technology, v. 89, n. 5-8, p. 1943-1958, 2017. DOI: 10.1007/s00170-016-9238-4	Published	2017	B1 / Impact factor: 1.568
	Relationships between modularity in design and production: a field study of two automobile manufacturers – Production Planning & Control.	Working paper (to be submitted in 2017)	2017	B1

Source: structure adapted from Machado (2015).

APPENDIX C – List of copyrights permissions from the papers presented in the doctoral thesis

In the next pages, the copyrights permissions and the declarations stating that copyrights were not requested (in conference papers' case) are presented.

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Best wishes
Tommaso Pardi

Tommaso Pardi
Directeur du GERPISA
Chargé de recherche au CNRS (IDHES)

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Bât Laplace
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Paper 2 and Paper 3 – Product: Management & Development

Re: Copyrights - Product (IGDP). Mensagem 18 de 6

De **Jose Carlos de Toledo**
Para **flavio.kubota@posgrad.ufsc.br**
Data **02.12.2015 17:48**

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autorizo o uso desses artigos, admitindo que vc é um dos co-autores, para fins de comporem o conjunto de artigos de sua tese de doutorado.

atenciosamente

prof josé carlos de toledo
editor da revista PMD

Em 02/12/2015 15:18, flavio.kubota@posgrad.ufsc.br escreveu:

> Prezado Prof. José Carlos de Toledo,
>
> Boa tarde. Aqui quem escreve é Flávio Issao Kubota, doutorando em Engenharia de Produção pela Universidade Federal de Santa Catarina (UFSC), sob orientação do Prof. Paulo Augusto Cauchick Miguel.
>
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>
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> DOI: http://dx.doi.org/10.4322/pmd.2013.006
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Reiner, Gerald <Gerald.Reiner@aau.at>
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Gerald Reiner

EurOMA 2015 conference chair

Paper 5 – International Journal of Advanced Manufacturing Technology

01_03

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August 8, 2016

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Your project

Requestor: Flávio Issao Kubota
flavioissao.kubota@gmail.com
University: Federal University of Santa Catarina - UFSC
Purpose: Dissertation/Thesis

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APPENDIX D – Questionnaire used in the empirical investigation

Data collection instrument (questionnaire)
Objectives:
1) To identify the adoption degree of modularity in the automotive industry
2) Analyze the relationships among the different modularity perspectives
3) Collect quantitative information to research projects' development

---

1. Information about the company
1.1. Name of the company ___________________________
1.2. Identify the position of your company in the supply chain, in case your company is not an automaker (you can mark more than one answer)
□ First-tier supplier (automaker's direct supplier)
□ Second-tier supplier (automaker's direct supplier and to other suppliers)
□ Second-tier supplier (supplier only connected to other suppliers)
□ Other levels, indicate: _______________________________________
1.3. Main responsible to fulfill this questionnaire: __________________
Position in the company: ______________________________________
Department: ____
Phone number: (_) _____ Time in the company: ____ years _____ months
E-mail: _________________________@_______________
1.4. What is the approximate number of employees in the company? ____
____
1.5. Approximate annual income (□ US$ or □ R$): __________________
____
Basis: Year ___________

---

2. Utilization of the modular approach
2.1. Does your company utilize modular strategy? (Please, select only one alternative)
□ Yes (go to question 3.1)
□ No (go to question 2.2a if it is na automaker or 2.2b if it is a supplier)
□ Implementing (go to question 3.1)
□ I do not have this information
2.2a. In case of the answer of the question 2.1 was "No", and the respondent company is an automaker, please indicate why the company never used modularity (you can choose more than one option):
□ Does not know the modularity concept
□ Difficulties to find suppliers capable to assemble the modules

□ Increase the dependence of the company on the other supply chain companies

□ Afraid of losing the Project control due to its development being conducted in various companies

□ Other reasons: ____

2.2b. In case of the answer of the question 2.1 was “No”, and the respondent company is a supplier, please indicate why the company never used modularity (you can choose more than one option):

□ Does not know the modularity concept

□ Your customers do not use modularity and for that reason the company does not need to apply it (modularity)

□ Increases labor costs

□ Increase the dependence of the company on the other supply chain companies

□ It needs a significant investment to implement

□ Other reasons: ____

3. Modularity implementation

3.1. How does your company defines modularity? (You can mark more than one option)

□ Product/Design (Consists of designing modular products defining modules, their functions and interfaces so that they are independent, but work on the product independently)

□ Production (Consists of simplifying manufacturing and assembly processes and may or may not transfer any of these activities to suppliers)

□ Organizational processes (consists of changing manufacturing processes and organizational procedures of the company as well as changes in the relationships with the suppliers, to adopt modular production)

□ Use (Consists in adapting the final product to customer requirements, modules’ changes, which can be optional or to enhance performance)

□ I do not have this information

□ Others (please, specify): ____________________________________

3.2. Based on the previous definitions, what are the types of modularity adopted in your company?

□ Product/Design □ Production □ Organizational processes □ Use □ I do not know

3.3. According to the modularity typology adopted by the company, already answered in question 3.2., please indicate: what departments are involved with the application of the types of modularity used in your company? (you can mark more than one option)

3.4. From what year was the modular strategy implemented? ___________

3.5. What are the modular products that your company manufactures? Please, list: ____

3.6. If the respondent company is a supplier, please specify who are the main customers who buy the manufactured modules and answer the question 3.7b; but if the respondent company is an automaker go to question 3.7a.

____

____

3.7a. Why did the automaker adopt the modular strategy? Indicate in a 0 to 4 scale the main reasons that led the company to adopt the modular approach. (0 – Totally disagree; 1 – Partially disagree; 2 – Neither disagree nor agree; 3 – Partially agree and; 4 – Totally agree). (Please select one option to each item in the list) (if possible, distribute the grades)

0 1 2 3 4 Reduce product complexity

0 1 2 3 4 Reduce the resources needed to develop the project (for instance: modules can be designed independently by suppliers)

0 1 2 3 4 Reduce lead-time

0 1 2 3 4 Increase product variety

0 1 2 3 4 Enables mass customization

0 1 2 3 4 Increase product flexibility

0 1 2 3 4 Reduce the assemble time

0 1 2 3 4 Reduce manufacturing costs because the modules are manufactured independently

0 1 2 3 4 Reduce direct labor in the assemble line

0 1 2 3 4 Reduce the number of suppliers

0 1 2 3 4 Other reasons (specify): ______________________________
____

3.7b. If the respondent company is a supplier, please indicate: why did the company adopt the modular strategy? Indicate in a 0 to 4 scale the main reasons that led the company to adopt the modular approach. (0 – Totally disagree; 1 – Partially disagree; 2 – Neither disagree nor agree; 3 – Partially agree and; 4 – Totally agree). (Please select one option to each item in the list) (if possible, distribute the grades)

0 1 2 3 4 To have long-term contracts with the automakers, which reduces the competition

0 1 2 3 4 To obtain exclusivity in supplying the automaker

0 1 2 3 4 To avoid losing market share (if the supplier not become a modular supplier)

0 1 2 3 4 Automaker and/or First-tier supplier demand, if the company is a supplier

0 1 2 3 4 Other reasons (specify): ______________________________
____

3.8a. If the respondent company is an automaker, please indicate in a 0 to 4 scale (0 1 2 3 4) the main problems found during the implementation of modular approach (0 – Totally disagree; 1 – Partially disagree; 2 – Neither disagree nor agree; 3 – Partially agree and; 4 – Totally agree). If the respondent company is a supplier go to question 3.8b (Please select one option to each item in the list) (if possible, distribute the grades):

0 1 2 3 4 Reduces the product performance due to the use of “generic” modules

0 1 2 3 4 To define the modularity method to be applied in the product

0 1 2 3 4 Risk of losing control of some projects, because the modules are designed separately

0 1 2 3 4 Redesign product and process

0 1 2 3 4 Increases the risk of sopping the assembly lines if there are delivery or quality issues

0 1 2 3 4 It can limit the modules' design to the suppliers' current capabilities to manufacture them

0 1 2 3 4 Find qualified suppliers to manufacture the modules

0 1 2 3 4 Change the supply from the traditional structure to modular structure

0 1 2 3 4 Transfer the less-important operations to suppliers

0 1 2 3 4 To conduct an organizational change to meet the modular strategy

0 1 2 3 4 High investment to reorganize the modular production

0 1 2 3 4 Other difficulties/limitations (specify): _____________

3.8b. If the respondent company is a supplier, please indicate in a 0 to 4 scale (0 1 2 3 4) the main problems found during the implementation of the modular approach (0 – Totally disagree; 1 – Partially disagree; 2 – Neither disagree nor agree; 3 – Partially agree and; 4 – Totally agree). If the respondent company is an automaker go to question 4.1 (Please select one option to each item in the list) (if possible, distribute the grades):

0 1 2 3 4 Define the modularity method to be applied in the product

0 1 2 3 4 Redesign product and process

0 1 2 3 4 Increases the risk of sopping the assembly lines if there are delivery or quality issues

0 1 2 3 4 Increases labor costs

0 1 2 3 4 Reduces economies of scale

0 1 2 3 4 Change the supply chain from traditional to modular

0 1 2 3 4 To develop the ability to attend the company in a synchronized way

0 1 2 3 4 To develop the ability to deliver the modules in the automaker's assembly line

0 1 2 3 4 To have flexible operations to meet customers' demands

0 1 2 3 4 The necessity of the company be geographically close to the automaker

0 1 2 3 4 Manage suppliers

0 1 2 3 4 To conduct an organizational change to meet the modular strategy

0 1 2 3 4 Transfer the less-important operations to suppliers

0 1 2 3 4 To become capable of manufacture the modules

0 1 2 3 4 Increases the dependence of the company on the automaker's decisions

0 1 2 3 4 High investment in the reorganization of the modular production

0 1 2 3 4 Other difficulties/limitations (specify): ____________
____

4. Application of modularity

4.1. Who defines the product specifications (project's technical characteristics) to satisfy the final user? (you can mark more than one option)

☐ The automaker ☐ The supplier (first-tier) ☐ Both

4.2. If the respondent applies modularity in design or modularity in use: what strategies are used to conduct product modularity? If the company does not use it, go to question 4.5. (you can mark more than option)

☐ Product strategies (consider the product structure or function)

☐ Supply chain strategies (consider if the automaker or the supplier will carry out the modules control)

☐ Product lifecycle strategies (consider the different product lifecycle phases)

☐ Market strategies (consider Market segments and demands)

☐ Other strategies (specify): ______________________________________

4.3. Who defines the strategies to modularize the product?

☐ The automaker ☐ The supplier (first-tier) ☐ Both

☐ Others (specify): ____

If possible, cite an example (if needed, use the final comments space):
____

4.4. What are the basis to define product modularity? (You can mark more than option)

☐ The customer ☐ The product functions ☐ The product structure

☐ The bill of materials

☐ Others (specify): ____

4.5. How does the company define the interfaces between the modules and the final product?

____

____

____

4.6. If the respondent company works with more than one modularity typology, are there relationships between those different types? (design, production, use and/or organizational)? If not, go to question 4.7. (please, mark only one of the options)

☐ Yes ☐ No

If yes, please specify: ____

4.7. Who conducts the modules production planning to attend the automaker's demand (please, select only one option)

☐ The automaker defines the production and delivery schedule of the modules

☐ The first-tier supplier defines the production and delivery schedule of the modules

☐ Both

☐ Others (specify): ______________________________________

5. Changes in the supply chain because of the modular approach

5.1a. If the respondent company is an automaker, please indicate in a 0 to 4 scale (0 1 2 3 4) the changes in the supply chain caused by the application of modularity (0 – Totally disagree; 1 – Partially disagree; 2 – Neither disagree nor agree; 3 – Partially agree and; 4 – Totally agree). If not, go to question 5.1b. (Please select one option to each item in the list) (if possible, distribute the grades):

0 1 2 3 4 It occurred the transfer, from the automaker to the supplier, of the modules' subassembly activities

0 1 2 3 4 It occurred the transfer, from the automaker to the supplier, of the modules' design activities (under automakers' guidance)

0 1 2 3 4 It occurred the transfer, from the automaker to the supplier, of the suppliers' management activities

0 1 2 3 4 It occurred the transfer, from the automaker to the supplier, of the modules' vehicle assembly

0 1 2 3 4 There was a provision of financial support from the assembler to the supplier to develop and/or produce the modules

0 1 2 3 4 There was a provision of expertise from the assembler to the supplier to develop and/or produce the modules

0 1 2 3 4 Others (specify) ___________________________

5.1b. If the respondent company is a supplier, please indicate in a 0 to 4 scale (0 1 2 3 4) the changes in the supply chain caused by the application of modularity (0 – Totally disagree; 1 – Partially disagree; 2 – Neither disagree nor agree; 3 – Partially agree and; 4 – Totally agree). If not, go to question 6.1. (Please select one option to each item in the list) (if possible, distribute the grades):

0 1 2 3 4 Secondary activities from your company have been transferred to your supplier.

0 1 2 3 4 There was a provision of financial support from the assembler to the supplier to develop and/or produce the modules

0 1 2 3 4 There was a provision of expertise from the assembler to the supplier to develop and/or produce the modules

0 1 2 3 4 Others (specify) __________________________________

6. Result

6.1a. If the respondent company is an automaker, please indicate in a 0 to 4 scale (0 1 2 3 4) the benefits in the application of modularity approach (0 – Totally disagree; 1 – Partially disagree; 2 – Neither disagree nor agree; 3 – Partially agree and; 4 – Totally agree). If not, go to question 6.1b. (Please select one option to each item in the list) (if possible, distribute the grades):

0 1 2 3 4 Reduced product complexity

0 1 2 3 4 Helped in developing new products by designing some new modules

0 1 2 3 4 Reduced project development time because the modules can be designed independently

0 1 2 3 4 Reduced design costs because modules can be designed independently

0 1 2 3 4 Improved quality of products delivered by suppliers

0 1 2 3 4 Improved product reliability

0 1 2 3 4 Facilitated product maintenance

0 1 2 3 4 It facilitated the updating of the product by the exchange of modules with new ones

0 1 2 3 4 Reduced product delivery time (final product, modules or sub-modules)

0 1 2 3 4 Increased production flexibility

0 1 2 3 4 Reduced manufacturing time because modules can be manufactured independently

0 1 2 3 4 Reduced assembly time because the modules can be manufactured independently

0 1 2 3 4 Reduced manufacturing costs

0 1 2 3 4 Reduced assembly costs by suppliers sub-assembling modules

0 1 2 3 4 Reduced direct labor at the automaker

0 1 2 3 4 Reduced assembly line size

0 1 2 3 4 Product variety has increased, by the exchange of some modules

0 1 2 3 4 Helped product customization

0 1 2 3 4 Made possible the involvement of suppliers in the automaker's manufacturing process

0 1 2 3 4 Increased the partnership between the assembler and the supplier by the participation of the suppliers in the development of new products together with the automaker

0 1 2 3 4 Reduced the number of suppliers

0 1 2 3 4 Reduced the number of items in stock

0 1 2 3 4 Others (specify) ________________________________

6.1b. If the respondent company is a supplier, please indicate in a 0 to 4 scale (0 1 2 3 4) the benefits in the application of modularity approach (0 – Totally disagree; 1 – Partially disagree; 2 – Neither disagree nor agree; 3 – Partially agree and; 4 – Totally agree). If not, go to question “Final comments” (Please select one option to each item in the list) (if possible, distribute the grades):

0 1 2 3 4 Reduced product delivery time (modules or sub-modules)

0 1 2 3 4 Increased the partnership between the assembler and the supplier by the participation of the suppliers in the development of new products with the automaker

0 1 2 3 4 It allowed the involvement of suppliers and distributors in the automaker's manufacturing process

0 1 2 3 4 Created opportunity to suppliers develop new skills, technology and processes

0 1 2 3 4 Created exclusive supply contracts for the supplier

0 1 2 3 4 Created long-term contracts between the assembler and the supplier, reducing competition

0 1 2 3 4 Others (specify) ______________________________

Final comments (free – please, use the space below and if needed the other side of this questionnaire final page):

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APPENDIX E – Interview protocol used in the empirical investigation

Modularity Interview protocol – Multiple case study

Researchers involved with the study:
Flávio Issao Kubota, MSc. (Federal University of Santa Catarina/Copenhagen Business School) – fik.om@cbs.dk[20]
Paulo Augusto Cauchick Miguel, PhD, Federal University of Santa Catarina (UFSC) – paulo.cauchick@ufsc.br
Juliana, Hsuan, PhD, Copenhagen Business School – jh.om@cbs.dk

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Dear Sir/Madam,

This is our research interview protocol, regarding application of modularity in design and production in automotive companies.

The concept of modularity has been increasing in the last years within the automotive sector, in order to enhance productive processes and product development process in the sector. In summary, modularity is an attribute of a complex system that advocates designing structures based on minimizing interdependence between modules and maximizing interdependence within them that can be mixed and matched in order to obtain new configurations without loss of the system's functionality or performance[21].

In this context, our research has the objective of analyzing how relationships between the application of modularity in design and modularity in production can contribute with the product development process as a whole in the automotive industry. In addition, if the cause and effect connections in these relationships are in fact necessary, and/or relevant for a better application of modularity concept.

Your participation in this research answering this interview protocol will be significantly important for our research, since we do not only analyze this topic in a theoretical perspective, but we also want to understand in practical, strategic and managerial perspective how relationships between modularity in design and in production can affect product management and development in the automotive industry.

Thank you so much for your participation and contribution.

With best regards,

The researchers.

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[20] Primary contact for any questions/suggestions about the research.

[21] Fonte: Campagnolo e Camuffo (2010) e Baldwin e Clark (1997).

1. Information about company

Date of the visit: ____DD ____MM _______ YYYY

1.1. **Company's name:** _______________________________________

1.2. **Name of the interviewed:** _________________________________

1.3. **Adjutancy in the company:** ________________________________

1.4. **Department:** ____

1.5. **Time in the company:** _____ years _____ months

1.6. **Telephone number:** _____________ **E-mail:** _____________

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2. Application of modularity and relationships between product modularity and production/process modularity

2.1. When did the company start to apply modularity?

□ 19__

□ 20__

2.2. What type or types of modularity does the company adopt?

□ Product/Design (Consists of designing modular products defining modules, their functions and interfaces so that they are independent, but work on the product independently)

□ Production (Consists of simplifying manufacturing and assembly processes and may or may not transfer any of these activities to suppliers)

□ Use (Consists in adapting the final product to customer requirements, modules' changes, which can be optional or to enhance performance)

2.3. In the case of your company, what are the main objectives and drivers that guide modularity application?[22] (Sanchez, 2013)

□ *Engineering issues* – Conventional development process using technical modularity to moderately reduce design time and cost

□ *Reduce product costs* – Early form of modular development process seeks to design (2A) *common components* and (2B) *re-usable components*

□ *Increase product variety* – Strategic partitioning decouples stable from variable components to enable low-cost configuration of product variations

□ *Reduce time to market* – Modular development process based on 'new rules and new roles' enables *concurrent component development*

□ *Knowledge management* – New architectural knowledge created in development is captured in *improved interface specifications*

□ *Strategic integration* – Architectural management function is directly involved in *setting market, technology, and business strategies*

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[22] Based on Sanchez (2013) – 'Building real modularity competence in automotive design, development, production, and after-service', Int. J. Automotive Technology and Management, Vol. 13, No. 3, pp. 204-236.

□ *Identifying and developing new strategic competences* – Architectural management function is directly involved in *identifying goals for strategic competence development*

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2.4. Which specifications and decisions regarding vehicle modules have influenced the manufacturing structure in terms of layout adjustments and need for additional investment in the unit?

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2.5. Which modules are part of the vehicle as a whole? How they are interconnected?

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2.6. If the company applies both product modularity and production modularity:

2.6.1. What modularity approach was developed first? Product modularity or production modularity?

□ Modularity in production systems → Modularity in product architecture

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□ Modularity in product architecture → Modularity in production systems

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2.6.2. Did the first modularity application lead to another modularity approach? (e.g. product modularity lead to production modularity or vice-versa)

- □ Yes (go to question 2.6.3)
- □ No (go to question 2.6.4)

2.6.3. What are the concepts that lead to this causal relationship?

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____
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2.6.4. Why it is not necessary establishing causal relationships between product modularity and production modularity?

2.7. Is it important to the company establishing causal relationships between product/design modularity and production modularity? Why?

2.8. How does the division of vehicle modules influence the intensity of the relationship between automaker and its suppliers?[23]

3. Please, if you want, write some final considerations about the interview and application of modularity in your company. Thank you for your support and information.

( ) Please, mark if you want to keep the company's name confidential.
Notes from the interview – Please, make your comments about this interview protocol here regarding questions' clarity, relevance and other critics / comments / suggestions to improve this data collection instrument. Thank you.

[23] Remember if suppliers are installed locally on the same plant or if there is a physical distance among them.